



Technology Assessment for the Future Aeronautical Communications System

ITT Industries
Reston, Virginia

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Preface

The following NASA Contractor Report documents the candidate technology prescreening process, and the associated findings and recommendations of ITT Industries and NASA Glenn Research Center to the Federal Aviation Administration (FAA) as of the end of December 2004. This work was completed under a NASA contract as the first phase of a multi-year technology assessment in support of an FAA/Eurocontrol Cooperative Research Agreement commonly referred to as the Future Communications Study. This work was performed in compliance with the Terms of Reference for that agreement and the general guidance of the FAA and Eurocontrol available throughout this initial phase of the study. Although officially released for distribution during the period of deliberations between the FAA and Eurocontrol that began in January 2005, these findings and recommendations do not reflect additional direction that has been received since the end of December 2004. NASA intends to publish a contractor report in the future that documents the second phase of the technology assessment and associated guidance from the FAA and Eurocontrol.

Technology Assessment for the Future Aeronautical Communications System

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Executive Summary

Air Traffic Management (ATM) communications capacity is reaching saturation in Europe and the United States. Europe has already begun a migration from 25 kHz channels to 8.33 kHz channels in the VHF aeronautical band to relieve congestion. The International Civil Aviation Organization (ICAO) is seeking a common global solution through its Aeronautical Communications Panel (ACP). In support of this, FAA and Eurocontrol have embarked on a joint study, with the support of NASA, to provide a major input to the ICAO ACP. Within the aegis of the FAA/Eurocontrol cooperative research and development program, Action Plan 17 (AP17-04) describes a joint framework to define a future Global Aeronautical Communications System (GACS) to support ATM operations.

Technical Theme 3 of AP17 calls for “investigation of potential communications technologies operating inside the VHF band and outside the VHF band to support the long-term mobile communication operation concept considering terrestrial and satellite base infrastructure.” In support of this objective, the Technology Pre-Screening Task 3.1 of AP17 outlined an activity to identify potential technologies that “are under development in the industry” and to assess their “high level capabilities, projected maturity for the time frame for usage in aviation, and their potential applicability to aviation.” In addition, AP17 defines a follow-on Technology Investigation Task 3.2 that determines those technologies that would meet the functional, performance and operational communications requirements for future ATM.

This report documents the technology assessment and recommendations of the Technology Pre-Screening Task 3.1 of AP17 described above. Figure E-1 illustrates the overall work flow of this Technology Pre-Screening study and its major elements. It includes a review of spectrum opportunities for aeronautical communications, development of evaluation criteria, and identification, evaluation and recommendation of technologies for further study. As such it identifies and recommends a set of communications technologies that should be brought forward for a more detailed technology assessment that will be undertaken as the major component of the future Technology Investigation Task 3.2.

As part of this Technology Pre-Screening study a wide variety of communications technologies were evaluated in each of the following technology groups:

- Cellular Telephony Derivatives
- IEEE 802 Derivatives
- Public Safety Radio
- Satellite and Over the Horizon Communications
- Custom Narrowband VHF
- Custom Wideband
- Military Communications

The technologies were evaluated in accord with a broad range of evaluation criteria that reflect the technical and strategic objectives that were defined for aeronautical communications at the 11th ICAO Air Navigation Conference in 2003. It is important to stress that the chosen evaluation criteria are the culmination of a process of collaboration, consensus and peer review among NASA, FAA, Eurocontrol, and their support contractors. The top level objectives embodied in the evaluation criteria are that the future communications system must

- 1) provide the communication capabilities that support current and emerging ICAO ATM concepts,
- 2) be technically mature and consistent with the requirements for aeronautical safety,
- 3) be cost beneficial, and
- 4) be consistent with spectral constraints and smooth transition.

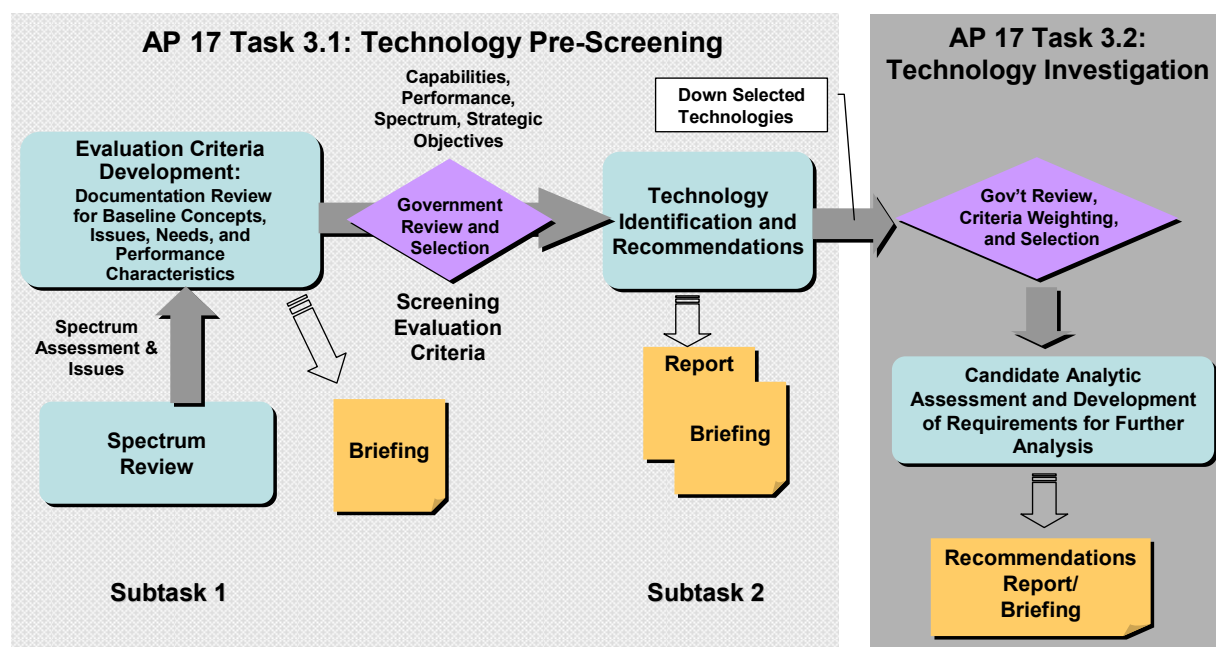


Figure E-1: Technology Assessment Work Flow

The primary technologies recommended for future study to provide communications over all continental airspace domains (enroute, terminal and surface) are:

- Project 34 (P34): P34 is a Electronic/Telecommunications Industries Association (EIA/TIA) standardized system for provision of wireless packet data services in a dispatch oriented topology for public safety service providers. The P34 standard is a result of a government (APCO—Association of Public-Safety Communications Officials) and commercial collaboration that specifically addresses “issues that restrict the use of commercial services for mission critical public safety wireless applications”
- VDL Mode 3: VDL Mode 3 is an integrated voice and data system base upon 25 kHz channelization.
- Broadband VHF (B-VHF): B-VHF is a development effort for a future aeronautical ATM communications system. The stated goal of the B-VHF project is to verify the feasibility of a broadband aeronautical communications system based on advanced RF technology at VHF and other aeronautical bands. The B-VHF Project is funded by the European Commission and a consortium of stakeholders, including research organizations, an airline, equipment vendors, and an ATM service provider.

A secondary technology recommended for study to provide communications over all continental airspace domains is:

- WCDMA: Wideband CDMA is a 3G cellular technology and the leading candidate among four other 3G systems that were evaluated. WCDMA provides the potential to be a good air/ground data system, but it is a highly complex system that will pose major challenges to integrate into the NAS architecture

The technologies recommended for study to provide communications over oceanic and polar airspaces are:

- Aero-BGAN: The Broadband Global Aeronautical Network is a system being built by Inmarsat consisting of three geosynchronous (GEO) satellites that provide communications service to mobile platforms. This constellation aims to support existing aeronautical safety services and Inmarsat has made a Public Service Agreement (PSA) commitment to ICAO. Current planning indicates that Aero-BGAN will commence providing voice and data services in 2006. Because it is provided via a GEO constellation, Aero-BGAN services will not be available in polar airspace.
- Iridium: Iridium is a commercial low-earth orbit satellite system being operated and maintained by Iridium Satellite LLC consisting of 66 low earth orbiting satellites in 6 orbital planes . Each satellite forms multiple beams which together form a footprint with a diameter of about 4500 km and thereby provide total global coverage. Iridium is currently providing voice and low data rate services.

A technology recommended for study to provide communications over the surface airspace domain is:

- IEEE 802.16: IEEE 802.16 is an evolving family of commercial specifications and products for wireless metropolitan area networks that is an outgrowth of the Ethernet standard. 802.16 supports fixed LoS and mobile NLoS communications and provides the aeronautical community the opportunity to use a COTS system for a broad scope of communications needs, both data and voice, in the airport surface domain.

Contents

1. Background and Introduction.....	1
1.1 Saturation of Aeronautical Communications Spectrum	1
1.2 Global Aeronautical Communications System Objectives	1
1.3 Spectrum Roadmap for Aeronautical Communications	2
1.4 Joint FAA/Eurocontrol Action	3
1.5 Purpose of This Report.....	3
2. Technology Assessment Approach.....	4
2.1 Overview of Work Flow.....	4
2.2 Evaluation Criteria and Metrics Development	5
2.2.1 Communications Capabilities—Voice.....	6
2.2.2 Communications Capabilities—Basic Data.....	8
2.2.3 Communications Capabilities—Expanded Data.....	10
2.2.4 Technology Readiness Level (TRL).....	11
2.2.5 Standardization	12
2.2.6 Certification	13
2.2.7 Cost: A/G Communications Infrastructure	13
2.2.8 Cost: Avionics.....	13
2.2.9 Spectrum Protection.....	13
2.2.10 Security	14
2.2.11 Transition.....	14
2.3 Technology Identification, Characterization and Evaluation	15
2.3.1 Technology Identification.....	15
2.3.2 Technology Characterization	16
2.3.3 Application of Minimum Threshold Test	16
2.3.4 Evaluation of Technologies in Accord with a Concept of Use.....	17
3. Technology Evaluations	18
3.1 Introduction to Technology Families	18
3.2 Cellular Telephony Derivatives.....	18
3.2.1 Overview of the Family	18
3.2.2 Selection of Evaluation Candidates via Minimum Threshold Test	23
3.2.3 Technology Description.....	23
3.2.4 Concept of Use: Application to Aeronautical A/G Communications.....	28
3.2.5 Evaluation Summary and Scores	32
3.3 IEEE 802 Derivatives.....	39
3.3.1 Overview of the Family	39
3.3.2 Selection of Evaluation Candidates via Minimum Threshold Test	41
3.3.3 Technology Description.....	42
3.3.4 Concept of Use: Application to Aeronautical A/G Communications.....	46
3.3.5 Evaluation Summary and Scores	48
3.4 Public Safety Radio	50

3.4.1	Overview of the Family	50
3.4.2	Selection of Evaluation Candidates	55
3.4.3	Project 25 and Project 34 Technology Descriptions.....	58
3.4.4	Concept of Use: Application to Aeronautical A/G Communications.....	74
3.4.5	Evaluation Summary and Scores	80
3.5	Satellite and Over the Horizon Communications.....	84
3.5.1	Overview of the Family	85
3.5.2	Selection of Evaluation Candidates via Minimum Threshold Test	89
3.5.3	Technology Descriptions	90
3.5.4	Concept of Use: Application to Aeronautical A/G Communications.....	98
3.5.5	Evaluation Summary and Scores	113
3.6	Custom Narrowband VHF.....	120
3.6.1	Overview of the Family	120
3.6.2	Selection of Evaluation Candidates via Minimum Threshold Test	124
3.6.3	Technology Description.....	125
3.6.4	Concept of Use: Application to Aeronautical A/G Communications.....	138
3.6.5	Evaluation Summary and Scores	142
3.7	Custom Wide Band	152
3.7.1	Overview of the Family	152
3.7.2	Selection of Evaluation Candidates via Minimum Threshold Test	152
3.7.3	Technology Description.....	152
3.7.4	Concept of Use: Application to Aeronautical A/G Communications.....	159
3.7.5	Evaluation Summary and Scores	161
3.8	Military Communications.....	170
3.8.1	Overview of the Family	170
3.8.2	Selection of Evaluation Candidates via Minimum Threshold Test	172
3.8.3	Technology Description.....	173
3.8.4	Concept of Use: Application to Aeronautical A/G Communications.....	181
3.8.5	Evaluation Summary and Scores	186
3.9	APC Telephony	190
3.9.1	Overview of the Family	190
3.9.2	Relevance to Operational (ATS and AOC) Aeronautical Communications.....	191
4.	Comparative Evaluation of All Candidates	191
4.1	Review of the Technology Families.....	191
4.2	Comparative Assessment Under Alternative Values Assumptions.....	195
4.2.1	Calculation of Composite Candidate Scores.....	195
4.2.2	Comparison of Composite Scores.....	196
4.2.3	Sensitivity Analysis	198
4.3	Summary of Analysis Observations	202
5.	Translating Analysis Into Pre-Screening Decisions	203
5.1	Review of the Roadmap for Future Aeronautical Communications	203
5.2	Efficient Technologies That Support Transition in VHF Band.....	204

5.3	Technologies That Use DME Spectrum.....	206
5.4	Technologies That Use MLS Spectrum	208
5.5	Technologies That Use AMS(R)S (Satellite)	209
5.6	Summary Conclusions.....	211
Appendix A—Bibliography.....		213
Appendix B—Evaluation Criteria and Metrics		223
Appendix C—NASA Requests for Information		229
Appendix D—Technology Characterization Form.....		235
Appendix E—List of Acronyms and Abbreviations		239
Appendix F—End Notes.....		247

1. Background and Introduction

1.1 Saturation of Aeronautical Communications Spectrum

Air Traffic Management (ATM) communications capacity is reaching saturation in Europe and the United States. Europe has already begun a migration from 25 kHz channels to 8.33 kHz channels in the VHF aeronautical band to relieve congestion. Various proposals have been offered and approved independently to provide adequate capacity for future voice and data communications, but none has achieved global endorsement. The International Civil Aviation Organization (ICAO) is seeking a common, global solution through the Aeronautical Communications Panel (ACP).

1.2 Global Aeronautical Communications System Objectives

At the 11th Air Navigation Conference (Sept/Oct 2003) of the International Civil Aviation Organization (ICAO), the following recommendations were made concerning a global solution for future aeronautical communications:

- Recommendation 7/4—Investigation of future technology alternatives for air-ground communications. That ICAO
 - investigate new terrestrial and satellite-based technologies, on the basis of their potential for ICAO standardization for aeronautical mobile communications use, taking into account the safety-critical standards of aviation and the associated cost issues;
- Recommendation 7/5—Standardization of aeronautical communication systems. That, for new aeronautical communication systems, ICAO
 - continue to monitor emerging communication systems technologies but undertake standardization work only when the systems meet all of the following conditions:
 - can meet current and emerging ICAO ATM requirements;
 - are technically proven and offer proven operational benefits;
 - are consistent with the requirements for safety;
 - are cost-beneficial;
 - can be implemented without prejudice to global harmonization of the CNS/ATM systems; and
 - are consistent with the *Global Air Navigation Plan for CNS/ATM Systems* (Doc 9750)

The primary functional objectives of the future aeronautical communications system are to:

- Relieve congestion in VHF spectrum by supporting a substantial increase in the number of voice channels by a) using VHF more efficiently, or b) using appropriate frequencies outside the VHF bands
- Provide communications (voice and data link) in all air spaces: enroute, terminal, surface, oceanic, and polar
- Provide sufficient voice and data communications capacity to support ATM operations through 2030 and beyond

The primary strategic objectives of the future system are also important. These are that:

- its cost is justified by a business case
- it is globally applicable/interoperable

- it allows a practical transition for service providers and airspace users
- it avoids needless different avionics equipments: multiple systems are acceptable to support communications in different airspaces, but should not be needed because of non-interoperable standards in different jurisdictions

Finally, the immediate schedule objectives for the future system are that it be ready to begin fielding in 2015 in order to relieve the current VHF frequency congestion in Europe and the United States.

1.3 Spectrum Roadmap for Aeronautical Communications

Available spectrum for Aeronautical Mobile (Route) Service [AM(R)S] is one of the driving constraints for the implementation of any new technology. Air Traffic Services (ATS) and Aeronautical Operational Control (AOC) support safety and regularity of flight and so require dedicated AM(R)S communications spectrum. ITU Radio Regulations Article 44 classifies such traffic into priority levels (1 to 6) and provides a clear illustration of the applicable message traffic as follows:

1. Distress calls, distress messages and distress traffic
2. Communications preceded by the urgency signal
3. Communications relating to radio direction-finding
4. Flight safety messages
5. Meteorological messages
6. Flight regularity messages

It should be noted that similar priority and preemption levels are also in ICAO Annex 10.

Current AM(R)S spectrum allocation for Air-Ground (A/G) communications is limited to the 118 to 137 MHz VHF band. In addition, Aeronautical Mobile Satellite (Route) Service [AMS(R)S] spectrum at L-Band may be used to support ATS and AOC. This spectrum includes segments of the overall mobile satellite allocation in the L-Band (1.545 to 1.559 MHz, 1610 to 1626.5 MHz, and 1.646.5 to 1.660.5 MHz in the U.S.).

The WRC-2007 Agenda Item 1.6 addresses additional AM(R)S allocations. One of the primary opportunities for such communications spectrum is to obtain co-primary AM(R)S allocations in those aeronautical radio navigation service (ARNS) bands where sharing is feasible between navigation and communications services. Where the current or future use of such bands for radio navigation is sparse, there is a practical feasibility for co-primary allocation to AM(R)S. One target band is in the 5 GHz region that is identified for the Microwave Landing System (MLS) and another, in the 1 GHz region, that is identified for Distance Measuring Equipment (DME). At the eighth meeting of the ICAO ACP/Working Group C (WGC8) in September 2004, the FAA presented its initial WRC-2007 recommendations regarding such opportunities¹. These were as follows.

- Pursue AM(R)S allocation [in DME band] should be limited to 960 to 1024 MHz
- Pursue AM(R)S allocation for 5091 to 5150 MHz band for airport local area systems

Given the competitive environment that exists for spectrum, the likelihood for gaining AM(R)S spectrum in the future from bands currently not allocated for aeronautical purposes is remote.

Because of the limited spectrum options and the fact that spectrum is such a driving constraint, it is useful to view the future roadmap for new A/G infrastructure as one defined by the technologies that are applied to the current and potential AM(R)S spectrum that is or may be available in the 2015 time frame. This roadmap is illustrated in figure 1.3-1. In accord with this roadmap, as technologies are assessed in this

report, a key part of the assessment will be its suitability for implementation in one or more of the applicable spectral bands. Furthermore, after all technologies are assessed and pre-screened, a primary output of this study is the presentation of this roadmap with the most promising technologies that are applicable to each spectral band.

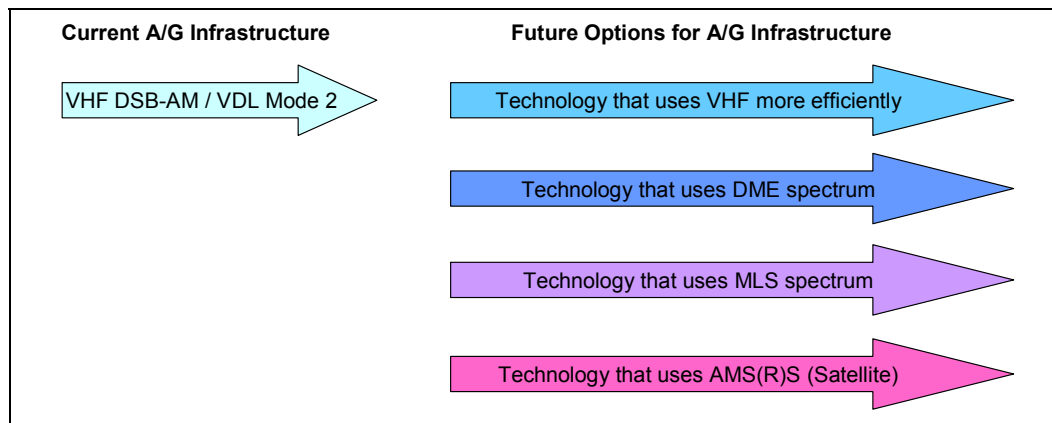


Figure 1.3-1: Initial Roadmap for Future Aeronautical Communications

1.4 Joint FAA/Eurocontrol Action

In support of this, FAA and Eurocontrol have embarked on a joint study, with the support of NASA, to provide a major input to ICAO ACP. Within the aegis of the FAA/Eurocontrol cooperative research and development program, Action Plan 17 (AP17-04) describes a joint framework to define a future Global Aeronautical Communications System (GACS) to support ATM operations. Technical Theme 3 of AP17 calls for “investigation of potential communications technologies operating inside the VHF band and outside the VHF band to support the long-term mobile communication operation concept considering terrestrial and satellite base infrastructure.” In support of this objective, Technology Pre-Screening Task 3.1 of AP17 outlined an activity to identify potential technologies that “are under development in the industry” and to assess their “high level capabilities, projected maturity for the time frame for usage in aviation, and their potential applicability to aviation.” In addition, AP17 defines a follow-on Technology Investigation Task 3.2 that determines those technologies that would meet the functional, performance and operational communications requirements for future ATM.

1.5 Purpose of This Report

This report documents the technology assessment and recommendations of the Technology Pre-Screening Task 3.1 of AP17 described above. As such it identifies and recommends a set of communications technologies that should be brought forward to a more detailed technology assessment that will be undertaken as the major component of the future Technology Investigation Task 3.2.

2. Technology Assessment Approach

2.1 Overview of Work Flow

The work flow for this technology assessment is illustrated in figure 2.1-1 below. Note that AP 17 Task 3.1 is divided into two subtasks as follows:

- Subtask 1 entailed a spectrum review to assess the feasibility and opportunities for obtaining spectrum for additional aeronautical communications. It also incorporated a review of ICAO, FAA, RTCA and Eurocontrol documentation on long range plans and future operations concepts to synthesize a set of screening evaluation criteria to apply to the candidate technologies identified in Subtask 2. The screening criteria were developed in close collaboration with Eurocontrol's contractor for AP17, QinetiQ, and were critiqued in the context of an FAA expert panel review. Separate briefings were conducted for NASA and the FAA on the results of the spectrum review, documentation review, and evaluation criteria development.
- Subtask 2 consisted of the identification of a large number of potentially applicable technology candidates, and subsequent characterization and pre-screening evaluation in accord with the evaluation criteria chosen in Subtask 1. The result of this evaluation is a set of down-selected technologies that are recommended for further study under AP17 Task 3.2.

Figure 2.1-1 illustrates that AP 17 Task 3.1 Technology Pre-Screening is the prelude to Task 3.2 Technology Investigation. Task 3.2 will absorb the outputs of pre-screening and, with FAA review, formally select technologies for detailed investigation and analysis.

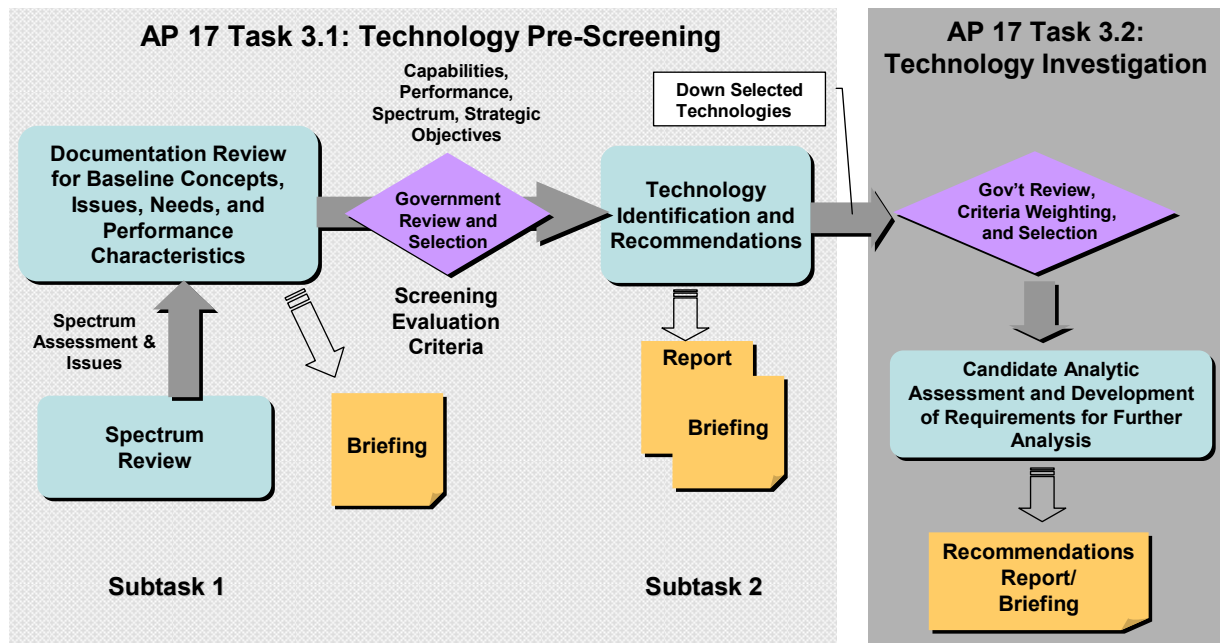


Figure 2.1-1: Technology Assessment Work Flow

2.2 Evaluation Criteria and Metrics Development

The chosen evaluation criteria illustrated in table 2.2-1 reflect a broad range of technical and strategic objectives that are traceable to the conditions for a new aeronautical communications system that were articulated at the 11th ICAO Air Navigation Conference and cited in section 1. The first three category rows of table 2.2-1 are in direct alignment with the guidance that a new system should provide communication capabilities that support current and emerging ICAO ATM concepts, be technically proven and consistent with the requirements for safety, and be cost-beneficial. The fourth category row incorporates other important criteria such as the availability of protected (Route) spectrum, security and accommodation of transition. Note that each evaluation category is broken down into multiple criteria. Additionally, the criteria within the category of communications capabilities are complex. As will be described below, they incorporate multiple sub-criteria that specifically address functional, capacity, and performance capabilities. A technology candidate is evaluated against each criterion or sub-criterion in accord with a metric that grades it as Green, Yellow, or Red, with Green representing the best rating. Note that there is no item #9: this refers to a criterion that was eliminated, but the numbering was not changed in accord with the policy of configuration management that was applied to the criteria.

Table 2.2-1: Evaluation Categories and Criteria

Category	Evaluation Category Description	Item #	Criteria
Communications Capabilities	Communication capabilities needed to support current and emerging ICAO ATM concepts	1	Meets Voice Needs
		2	Meets Basic Datalink Needs
		3	Meets Expanded Datalink Needs
Maturity for Aeronautical Environment	Technical maturity as well as the recognition for the safety assurance required for aeronautical standardization and certification	4	Technology Readiness Level
		5	Standardization
		6	Certification
Cost	Cost of infrastructure used by the service provider as well as the cost of avionics equipage by aircraft	7	A/G Communications Infrastructure
		8	Avionics
Other	Availability of suitable AM(R)S spectrum, support for security, and practical accommodation of transition	10	Spectrum Protection
		11	Security
		12	Transition

It is important to note that the chosen evaluation criteria and the metrics are the culmination of process of collaboration and peer review among the technology assessment groups (NASA and ITT for FAA; QinetiQ for Eurocontrol), a requirements identification group, and an FAA panel of experts. This process is illustrated in figure 2.2-1 and shows the three paths that influenced the evaluation criteria. The top path indicates that the evaluation criteria were developed with full awareness of the efforts of the Operational Concepts and Requirements Team in developing the Initial Communication Operating Concept and Requirements (ICOOCR). The bottom path illustrates the involvement of the FAA's Operational Environment of Transition Analysis (RTTA) Team of experts.

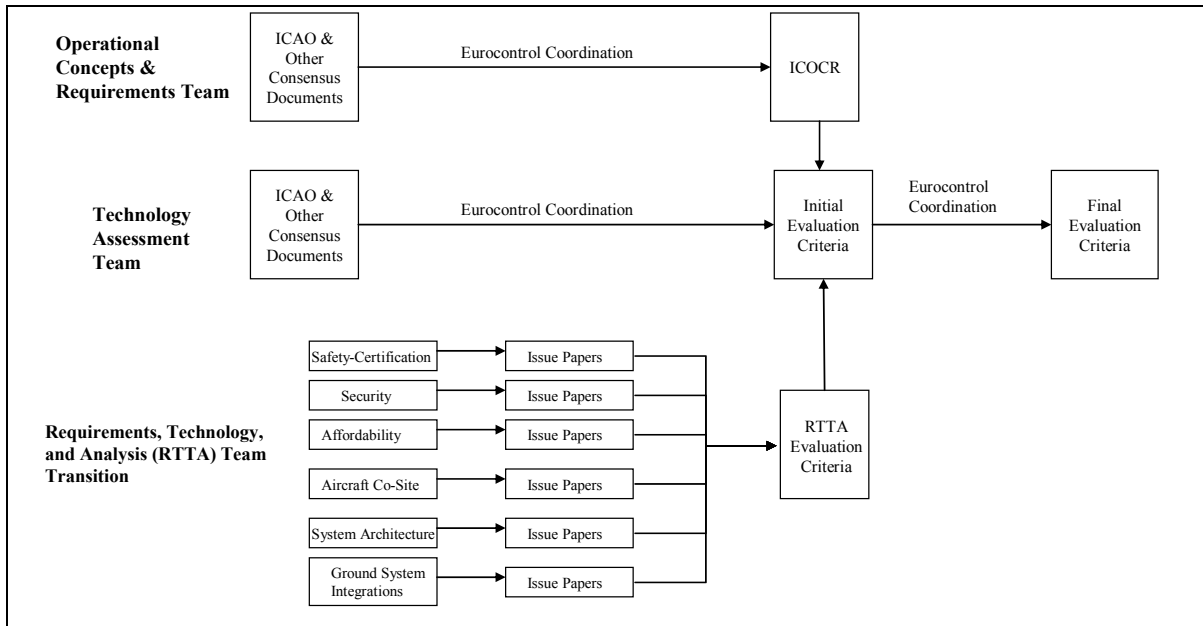


Figure 2.2-1: Evaluation Criteria Development Process

The middle path indicates the effort of the Technology Assessment Team to develop a set of evaluation criteria based upon a set of core documentation issued by the ICAO, RTCA, FAA and Eurocontrol that address future ATM concepts and their required communications support. Table 2.2-2 provides a list of core documentation that provided background information on future ATM concepts and associated voice and data communications services.

Table 2.2-2: Core Documentation

Document	Issuer
Global Air Navigation Plan for CNS/ATM Systems (Doc 9750)	FAA
Global ATM Operational Concept Document—AN-Conf/11-WP/4	ICAO
ATM Strategy for the Years 2000+, 2003 Ed.	Eurocontrol
EATMP Communications Strategy, August 2003	Eurocontrol
Operating Concept of the Mobile Aviation Communication Infrastructure Supporting ATM Beyond 2015 (MACONDO—2002)	Eurocontrol
NAS Concept of Operations and Vision for the Future of Aviation, 2002	RTCA
Initial Communication Operating Concept and Requirements (ICOCR) for the Future Communications System—December 2004	FAA/Eurocontrol

Finally, because the evaluation criteria and metrics represent a broad consensus, they were placed under FAA configuration management for some months, and have been incrementally modified occasionally as the consensus deemed appropriate. The complete controlled document is placed in Appendix B. However, for convenience, each criterion in the above table is discussed in distinct subsections and the controlled document has been broken out into many pieces.

2.2.1 Communications Capabilities—Voice

The Voice capabilities criterion for a future communications system is partitioned into three groups of sub-criteria that relate to the ability of a system to provide:

- Functional Capabilities
- Capacity Capabilities
- Performance Capabilities

The Voice Functional Capabilities, described in table 2.2-3 relate to the ability of a system to provide a set of four voice services. Note that except for few *italicized text* insertions for clarification, the table is a direct copy of the evaluation criteria and metric document under configuration management (CM) by the FAA and included in Appendix B. The pilot-controller talk group service is essentially today's party line service with AM voice. Pilot-pilot communications today is also via party line voice, but a future system could provide the same functionality, but with a different implementation. Pilot-Controller selective addressing is a new service that is envisioned in the future when substantial situational awareness is provided via data link means. At such time, a crowded party line may likely provide no additional value and furthermore, could serve to distract the pilot with irrelevant chatter. At such time, a selective addressed service may be of value, in which the controller chooses a specific pilot to give direction to and the dialog is not overheard by other pilots in the vicinity.

Table 2.2-3: Voice Functional Capabilities

A. Functional Capabilities: Supported Voice Services
<p>1. Pilot-Controller Talk Group: this is essentially the setup and maintenance of a group conference call between a Controller and all of the Pilots in the domain of that Controller.</p> <p>Assessed as: Green—The candidate required no modifications; the candidate has already demonstrated/validated this capability; or, The candidate requires very small and/or low risk modifications. Yellow—The candidate requires moderate modifications in order to meet this criterion. Red—The candidate can not reasonably implement this capability with moderate modification(s).</p>
<p>2. Pilot-Controller Selective Addressing: supports a call and dialog between a Controller and a selected Pilot that is not overheard by other Pilots</p> <p>Assessed as: Green—The candidate required no modifications; the candidate has already demonstrated/validated this capability; or, The candidate requires very small and/or low risk modifications. Yellow—The candidate requires moderate modifications in order to meet this criterion. Red—The candidate can not reasonably implement this capability with moderate modification(s).</p>
<p>3. Direct Pilot-Pilot: the candidate allows Pilots to talk directly with each other without requiring other facilities as an intermediary.</p> <p>Assessed as: Green if the candidate is using only aircraft equipment (<i>i.e., no intermediary</i>) Yellow if ground or space equipment is required and Red, if the candidate could not do the function.</p>
<p>4. Broadcast capability. The technology provides a voice broadcast capability. <i>Means that an appropriately tuned aircraft can listen to a broadcast channel and have broadcast access to it when the channel is idle.</i></p> <p>Assessed as: Green—The candidate requires no modifications; the candidate has already demonstrated/validated this capability; or, The candidate requires very small and/or low risk modifications in order to meet this criterion. Yellow—The candidate requires moderate modifications in order to meet this criterion. Red—The candidate can not reasonably implement this capability with moderate modification(s).</p>

The Voice Capacity Capabilities, described in table 2.2-4 relate to the ability of a system to provide an increase in capacity and sufficiently large address space to accommodate a worst case talk group (i.e., surface at Chicago O'Hare). The criterion of a notional doubling of capacity ensures that only candidates that have significant potential to relieve the congestion of voice channels will be considered. Note that the numbering scheme is populated by some items that have been deleted after CM was put in place.

Table 2.2-4: Voice Capacity Capabilities

B. Capacity Capabilities
<p>1. Capacity provided: The candidate supports a significant increase in communications capacity.</p> <p>Assessed as: Green—The candidate supports a notional doubling of capacity. Yellow—The candidate supports a moderate increase in capacity. Red—The candidate has, at best, marginally more capacity.</p>
<p>2. [Item Deleted]</p>
<p>3. Address space. The candidate supports a sufficient number of addressed users per talk group.</p> <p>Assessed as: Green—The candidate supports greater than 200 addressed users per talk group. Note: 200 addressed users based on Chicago surface aircraft number. Yellow—The candidate supports between 30 and 200 addressed users per talk group. Red—The candidate supports less than 30 addressed users per talk group. Note: 30 addressed users based on RTCA DO-290.</p>

The Voice Performance Capabilities, described in table 2.2-5 relate to the ability of a system to support mobility management, and to provide for low latency end-to-end voice. In judging a systems ability to support mobility management, Green was awarded if the system supports the function automatically, while Yellow was awarded if the function could be supported by manual procedures. The thresholds for voice latency come from the FAA SR-1000 voice requirement and a reasonable value for one-way end-to-end latency over a geostationary satellite link. In the context of SR-1000, voice latency is simply the end-to-end delay of a voice stream once a channel is seized via the push-to-talk (PTT) protocol. However, it is also important to be mindful of the fact that the time required to seize a channel (i.e., the time between the PTT event and channel access) is also an important parameter. Accordingly, for the latency criteria, we evaluated the total latency, which includes the channel access time as well as the delay of the voice stream.

Table 2.2-5: Voice Performance Capabilities

C. Performance Capabilities for Pilot Controller Voice Services
<p>1. Aircraft mobility management: should dynamically manage Talk Groups as aircraft members join and leave. The intent of this is that a candidate can add or subtract users without denial of service (to remaining talk group members) and without unacceptable additional controller/pilot workload—<i>note that although this is in a performance table, it has been treated more properly as a functional category in this assessment.</i></p> <p>Assessed as: Green—The candidate required no modifications; the candidate has already demonstrated/validated this capability; or, The candidate requires very small and/or low risk modifications. Yellow—The candidate requires moderate modifications in order to meet this criterion. Red—The candidate can not reasonably implement this capability with moderate modification(s).</p>
<p>2. Latency: The candidate should have acceptable one-way end-to-end voice latency</p> <p>Assessed as: Green—Less than or equal to 250 ms one way. Yellow—More than 250 ms and less than 400 ms one way. Red—Greater than or equal to 400 ms one way.</p>

2.2.2 Communications Capabilities—Basic Data

The Basic Data capabilities criterion for a future communications system is partitioned into three groups of sub-criteria that relate to the ability of a system to provide:

- a. Functional Capabilities
- b. Capacity Capabilities
- c. Performance Capabilities

The Basic Data Functional Capabilities, described in table 2.2-6 relate to the ability of a system to provide both addressed and broadcast data services for both air traffic control (ATS) and aeronautical operations (AOC), as defined by the ICAO Global Plan². Addressed service would support such applications as the Controller Pilot Data Link (CPDLC) and broadcast service would support such applications as Flight Information Service (FIS-B).

Table 2.2-6: Basic Data Functional Capabilities

A. Functional Capabilities: Supported Data Services
1. Air-to-Ground and Ground-to-Air Addressed Data Transport <u>Assessed as:</u> Green—The candidate required no modifications; the candidate has already demonstrated/validated this capability; or, The candidate requires very small and/or low risk modifications. Yellow—The candidate requires moderate modifications in order to meet this criterion. Red—The candidate can not reasonably implement this capability with moderate modification(s).
2. Ground-to-Air Broadcast Data Transport <u>Assessed as:</u> Green—The candidate required no modifications; the candidate has already demonstrated/validated this capability; or, The candidate requires very small and/or low risk modifications. Yellow—The candidate requires moderate modifications in order to meet this criterion. Red—The candidate can not reasonably implement this capability with moderate modification(s).

The Basic Data Capacity Capabilities, described in table 2.2-7 relate to the ability of a system to provide a targeted aggregate data rate and a sufficient number of addressed users in a sector. The aggregate data rate may be that of a single physical channel that serves a user group as well as multiple grouped channels, if that capability is provided by the system. The Green level relates to the current signaling rate for VDL 2, while the Yellow level relates to the signaling rate for the Aircraft Communication Addressing and Reporting System (ACARS).

Table 2.2-7: Basic Data Capacity Capabilities

B. Capacity Capabilities
1. Aggregate Data Rate. This criterion assesses the data throughput provided to a user group. The bit rates below are aggregate and include all transmitted bits. The assessment is whether the aggregate data rate to and from aircraft in a user group is acceptable. Should a distinction between average and peak be required (technology specific detail) then the analyst annotation should explain what is being evaluated and why. <u>Assessed as:</u> Green—Greater than or equal to 31.5 kbps per user group (per MACONDO rate estimate). Yellow—Greater than or equal to 2.4 kbps and less than 31.5 kbps per user group. Red—Less than the equivalent of today's VDL service (i.e., less than 2.4 kbps).
2. Number of Users. The number of users that can receive addressed data services in a user group is acceptable. <u>Assessed as:</u> Green—The candidate supports greater than 200 addressed users per user group. Yellow—The candidate supports between 30 and 200 addressed users per user group. Red—The candidate supports less than 30 addressed users per user group.

The Basic Data Performance Capabilities, described in table 2.2-8 relate to the ability of a system to provide for different priority levels and low latency. Judging a system's ability to provide priority levels at a defined Quality of Service (QoS) is based primarily on whether the Medium Access Control (MAC) layer of the air interface supports a robust and deterministic reservation access scheme. Judging a system's ability to provide the target latency was based upon an assumption of a lightly loaded system, not on its performance in the context of a defined traffic model that could create congestion and degrade the delay performance.

Table 2.2-8: Basic Data Performance Capabilities

C. Performance Capabilities for Data Transport
<p>1. Uplink and Downlink Priority Levels/QoS: service supports priority levels such that traffic at a lower priority does not degrade higher priority traffic beyond its required QoS.</p> <p>Assessed as: Green—The candidate required no modifications; the candidate has already demonstrated/validated this capability; or, The candidate requires very small and/or low risk modifications. Yellow—The candidate requires moderate modifications in order to meet this criterion. Red—The candidate can not reasonably implement this capability with moderate modification(s).</p>
<p>2. Latency. Be consistent with the end-to-end latency requirements by classes of traffic as specified for ICAO Annex 10, Volume III, Part 1, Chapter 3 covering the ATN</p> <p>Assessed as: Green—Meets ATSC Class B (4.5 sec at 95% assurance) Yellow—Meets ATSC Class C (7.2 sec at 95% assurance) Red—Meets ATSC Class D or lower (13.5 sec at 95% assurance)</p>

2.2.3 Communications Capabilities—Expanded Data

The Expanded Data Functional Capabilities, described in table 2.2-9 relate to the ability of a system to support ADS-B, pilot-pilot data transactions functions, and support a significant larger data rate for ATS and AOC beyond than associated with Basic Data. We explicitly assumed that a candidate must support direct air-air communications to support the ADS-B function. However, in assessing pilot-pilot data transport (item 2 in the table), we have judged systems as Green that provide direct air-air data with no intermediary, and Yellow with an intermediary, and Red if they cannot perform the function. This is analogous to the way the metric was applied for air-air voice.

Table 2.2-9: Expanded Data Functional Capabilities

A. Functional Capabilities: Expanded Data
<p>1. ADS-B.</p> <p>Assessed as: Green—The candidate required no modifications; the candidate has already demonstrated/validated this capability; or, The candidate requires very small and/or low risk modifications. Yellow—The candidate requires moderate modifications in order to meet this criterion. Red—The candidate can not reasonably implement this capability with moderate modification(s).</p>
<p>2. Pilot-Pilot Data Transport: the candidate allows Pilots to exchange data with each other. It is not necessary that this function be provided as a direct avionics-to-avionics transport. An intermediary is acceptable when provisioning this service.</p> <p>Assessed as: Green—The candidate required no modifications; the candidate has already demonstrated/validated this capability; or, The candidate requires very small and/or low risk modifications. Yellow—The candidate requires moderate modifications in order to meet this criterion. Red—The candidate can not reasonably implement this capability with moderate modification(s).</p>

The Expanded Data Capacity Capabilities, described in table 2.2-10 relate to a larger aggregate data rate than required for Basic Data. Expanded data includes all Basic Data plus all air-air data as well as additional capacity to accommodate advanced ATM concepts for which the message traffic is speculative but potentially large (e.g., System Wide Information Management) applications and network centric operations. The aggregate data rate may be that of a single physical channel that serves a user group as well as multiple grouped channels, if that capability is provided by the system. They relate to a user group with 200 aircraft. Thus, the Green and Yellow levels correspond to data rates of 10 kbps and 1.4 kbps per aircraft, respectively.

Table 2.2-10: Expanded Data Capacity Capabilities

B. Capacity Capabilities	
<p>1. Aggregate Data Rate. This criterion assesses the data throughput provided to a user group. The bit rates below are aggregate and include all transmitted bits. The assessment is whether the aggregate data rate to and from aircraft in a user group is acceptable. Should a distinction between average and peak be required (technology specific detail) then the analyst annotation should explain what is being evaluated and why.</p>	
Assessed as:	
Green—Greater than or equal to 2 Mbps per user group	
Yellow—Greater than 280 kbps and less than 2 Mbps per user group.	
Red—Equal to or less than 280 kbps	

2.2.4 Technology Readiness Level (TRL)

The TRL scale was used as a criterion to evaluate the technical maturity of a candidate technology. The TRL scale as an evaluation of the readiness of technologies was pioneered by NASA and has been adopted by the DoD. The TRL is a measure of the gap between a technology's current maturity and the maturity needed for successful implementation. The TRL scale, illustrated in figure 2.2-3, ranges from 1 to 9, based upon objective criteria. In figure 2.2-4, the TRL is compared and mapped to the FAA's Implementation Readiness Level (IRL) and indicates what needs to be done and a time schedule from a given TRL to an operational system.

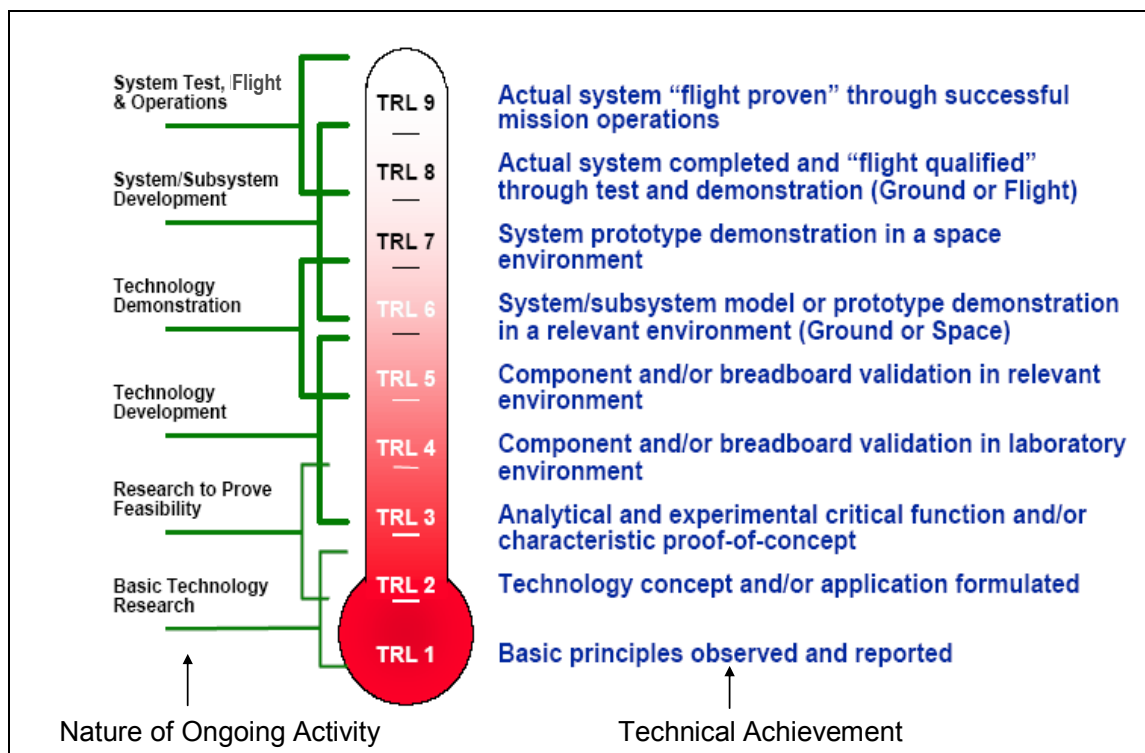


Figure 2.2-3: Technology Readiness Level Scale

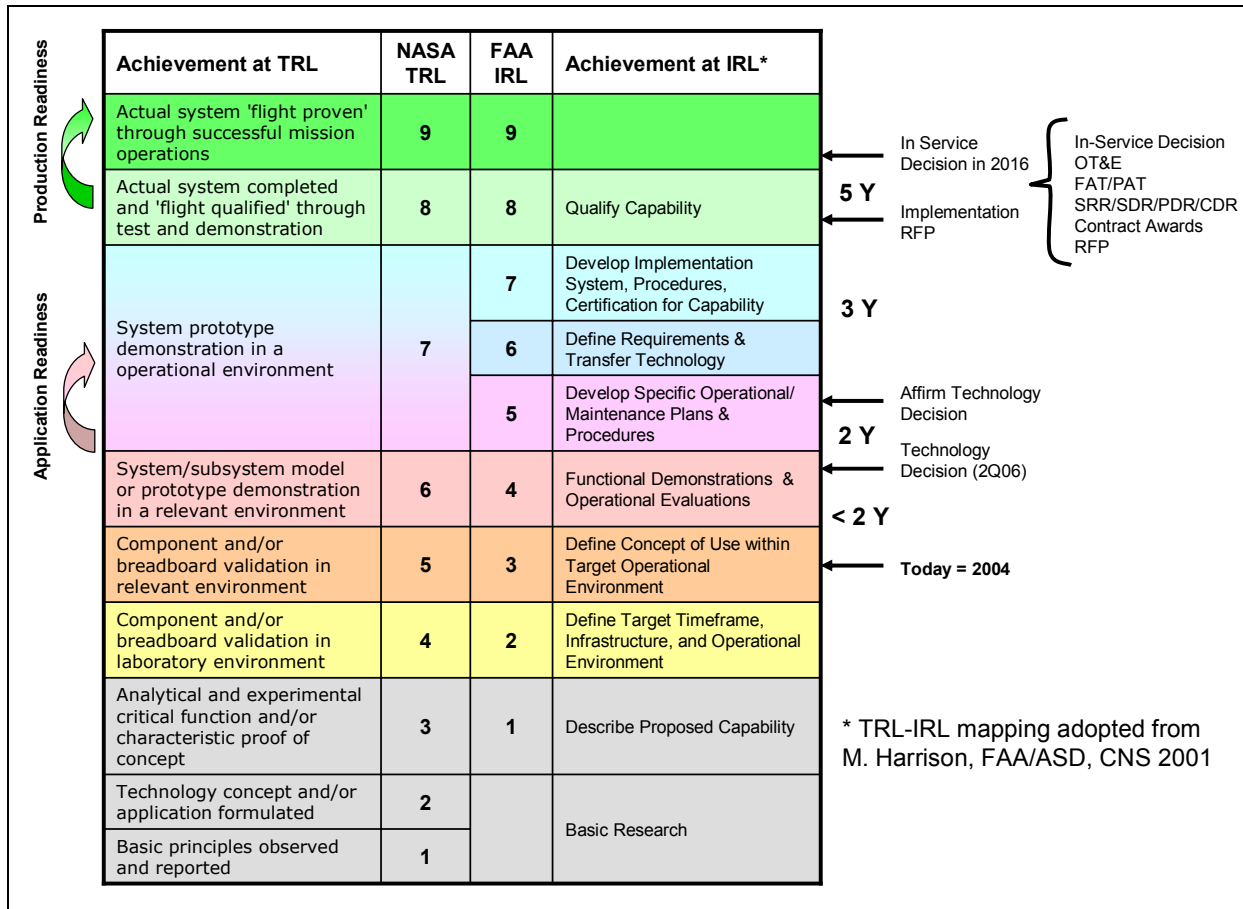


Figure 2.2-4: TRL and IRL Scales Compared

The TRL criterion was used in this study to evaluate the technical maturity in the aeronautical environment. Table 2.2-11 describes how the TRL is mapped into the evaluation colors.

Table 2.2-11: Technology Readiness Level

Technology Readiness Level
[G, Y, or R status is assigned by assessing the TRL of the proposed candidate.]
Assessed as:
Green is a TRL 6 or above
Yellow is TRL 5-4
Red is TRL 3 and below

2.2.5 Standardization

Table 2.2-12 illustrates how the standardization status was used and mapped into the evaluation colors.

Table 2.2-12: Standardization

Standardization Status
[G, Y, or R status is assigned based upon the existence of applicable standards for the candidate]
Assessed as:
Green: candidates that have a publicly available aeronautical standard;
Yellow: candidates are supported by a mature commercial standard
Red: candidates for which a supporting standard does not exist or is not publicly available

2.2.6 Certification

Table 2.2-13 illustrates how the certification status was used and mapped into the evaluation colors.

Table 2.2-13: Certification

Certiability
Measure of certification risk Assessed as: Green: Candidates developed for the aviation industry and either currently certified or known to be in the certification process Yellow: Candidates developed for safety related services (Public safety and the like) but not currently in the aviation certification process Red: All other candidates

2.2.7 Cost: A/G Communications Infrastructure

Table 2.2-14 illustrates how the estimate of infrastructure cost was used and mapped into the evaluation colors.

Table 2.2-14: Cost: A/G Infrastructure

A/G Infrastructure Cost
Relative cost to replace or upgrade infrastructure with the necessary availability and diversity requirements for critical services, as a replacement to VHF DSB-AM; where applicable, replacement of a ground station covering a large area (e.g., high enroute sector) should be assessed: thus, a candidate not able to project a signal at a large range from a single ground station would require multiple replacement ground stations; this naturally penalizes candidates that cannot practically project a signal at a large range. The evaluation will include any unusual maintenance requirements of a candidate (to include leased services, maintenance of Network Operational Centers, extraordinary Telco bandwidth requirements and the like). Assessed as: Green: low relative cost, Yellow: moderate relative cost, Red: high relative cost

2.2.8 Cost: Avionics

Table 2.2-15 illustrates how the estimate of avionics cost was used and mapped into the evaluation colors.

Table 2.2-15: Cost: Avionics

Cost to Aircraft
Relative cost to upgrade avionics with new candidate voice and data link technology but maintain VHF DSB-AM capability; Assessed as: Green: low relative cost Yellow: moderate relative cost Red: high relative cost

2.2.9 Spectrum Protection

Table 2.2-16 illustrates how the spectrum status was used and mapped into the evaluation colors. The evaluation pertains to the likelihood that the targeted spectrum for a candidate technology will be available for aeronautical communications.

Table 2.2-16: Spectrum Protection

Spectrum Protection
<p>[G, Y, or R status is assigned based upon the extent to which the potential frequency bands are consistent with aeronautical safety critical communications]</p> <p>Assessed as:</p> <p>Green: the target band for the alternative has a global allocation for the Aeronautical Mobile (route) Service (AM(R)S) for ground-based systems or Aeronautical Mobile Satellite (route) Service (AMS(R)S) for satellite-based systems, as applicable</p> <p>Yellow: it can be reasonably expected that an additional global allocation (AM(R)S for terrestrial or AMS(R)S for satellite-based) could be added to the target band or if the band is shared with other aviation systems, it is feasible that appropriate frequency assignment criteria could be developed within ICAO that would prevent interference with the other aviation systems.</p> <p>Red: All other circumstances</p>

2.2.10 Security

Table 2.2-17 illustrates how the security capabilities of a technology were used and mapped into the evaluation colors.

Table 2.2-17: Security Capabilities

Security
<p>[G, Y, or R status is assigned based upon the extent to which candidate supports authentication and integrity].</p> <p>Assessed as:</p> <p>Green: candidate supports A and I</p> <p>Yellow: candidate can be modified to support A and I.</p> <p>Red: candidate cannot be modified to support A and I.</p>

2.2.11 Transition

Table 2.2-18 illustrates how the ability of a technology to accommodate transition was used and mapped into the evaluation colors.

Table 2.2-18: Transition

Transition
<p>The candidate must have acceptable transition characteristics, including:</p> <ul style="list-style-type: none"> • return on partial investment • ease of technical migration (spectral, physical) • ease of operational migration (air and ground users) <p>Assessed as:</p> <p>Green candidate:</p> <ul style="list-style-type: none"> • provides return on investment (i.e. service provision/benefit) without requiring full/complete investment /deployment, and • can be operated simultaneously (in adjacent airspace) with legacy A/G comm. system (i.e. you can bring the new system up incrementally, while bringing the legacy system down incrementally), and • initial transition can be nearly operationally transparent (i.e. initially, users do not have to significantly alter procedures) or features that drive changes in operational procedures can be employed incrementally <p>Yellow candidate: can have no attributes of a Red candidate</p> <p>Red candidate:</p> <ul style="list-style-type: none"> • provides little or no return on investment (i.e. service provision/benefit) until full/complete investment /deployment, or • requires operation of legacy A/G comm. system be widely discontinued in order to operate, or • initial transition requires significant changes to operational procedures.

2.3 Technology Identification, Characterization and Evaluation

Figure 2.3-1 illustrates the overall process for identification, characterization, and evaluation of candidate technologies for the future aeronautical communications system. Each of these is described in the following subsections.

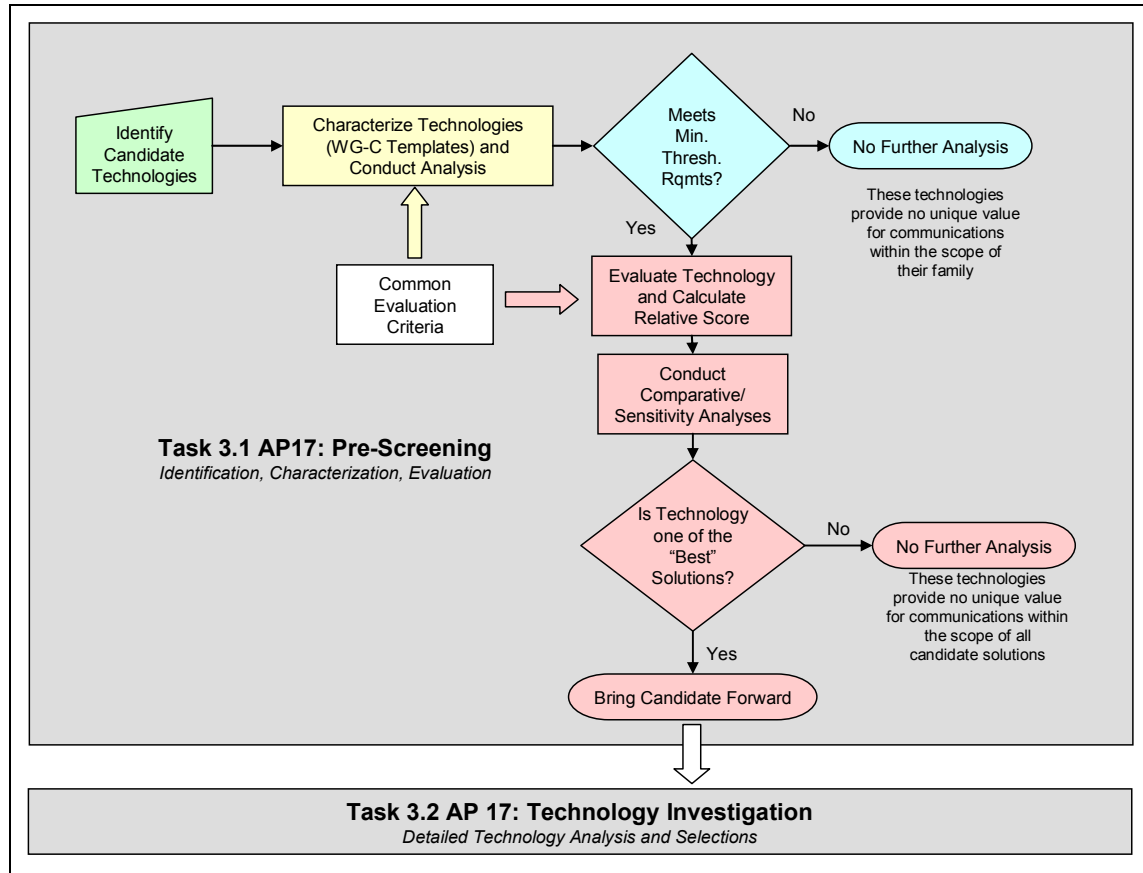


Figure 2.3-1: Process for Technology Pre-Screening

2.3.1 Technology Identification

In order to identify the complete scope of technologies that may be applicable, a three pronged approach was used for technology identification:

- A survey of widely used and successful commercial and military technologies was conducted to identify technologies that offered potential value to A/G communications
- NASA released two Requests for Information (RFI) soliciting technology candidate inputs from industry (included in Appendix C)
- Technology candidates previously identified by the ICAO ACP WG-C were included in this study

In all, over 50 technology candidates were identified in this process.

2.3.2 Technology Characterization

Characterization involves the collection of basic information about each technology candidate, prior to analysis and evaluation for the aeronautical application. Where practical, identified technologies were characterized in accord with the form contained Appendix D. The form is an adaptation of a standard characterization form developed by the ICAO ACP WG-C. It contains all the information of the ACP form plus additional information that is needed to conduct the evaluations in accord with the chosen evaluation criteria.

2.3.3 Application of Minimum Threshold Test

Because of the large number of candidate technologies identified, it is important to have an efficient evaluation process. A key element of such a process is to filter out technologies that provide insufficient value, or whose value is clearly surpassed by comparable alternatives without going through the entire evaluation process. This is indicated in figure 2.3-1 where a minimum threshold test is applied. A key element of this approach is the grouping of technology candidates into families as illustrated in Table 2.3-1, which lists all identified technology candidates in accord with their family grouping. A family is defined by similarity of the application and/or the technology heritage. Grouping technologies into families is a useful simplification because it collapses the large number of identified candidates into eight families. The candidate technologies in each family are compared with each other in order to select a subset for further evaluation. The subset within a family is selected based upon a rough assessment of the relative value of each technology to aeronautical communications and the application of the following criteria:

- A proprietary technology was eliminated if another technology in the family that is based on an open standard provides comparable value
- An immature technology was eliminated if a more mature technology in the family offered equal or greater value
- An older (near end of life) technology was eliminated if a successor mature technology in the family provided equal or greater value with no expected cost impact
- A technology candidate that intrinsically uses unprotected spectrum {i.e., not AM(R)S or AMS(R)S} was eliminated
- A technology was eliminated if another technology in the family provided equal value and was more widely implemented
- A technology was eliminated if it could not support a practical transition. This comes into play primarily for implementation of candidates in the VHF band

Table 2.3-1 illustrates the wide range of technologies identified. In section 3, the candidates in each of these families will be described appropriately.

Table 2.3-1: Technology Candidates Grouped by Families

Technology Family	Candidate Solutions
Cellular Telephony Derivatives	TDMA (IS-136), CDMA (IS-95A), CDMAone (IS-95B), CDMA2000 1xRTT, W-CDMA, TD-CDMA, CDMA2000 3x, CDMA2000 1xEV, GSM/GPRS/EDGE, TD-SCDMA, DECT
IEEE 802 Derivatives	IEEE 802.11, IEEE 802.15, IEEE 802.16, IEEE 802.20, ETSI HIPERLAN, ETSI HIPERMAN
Public Safety Radio	APCO P-25 Phase 1, APCO P-25 Phase 2, TETRA Release 1, TETRAPOL, IDRA, IDEN, EDACS, APCO P-34, TETRA Release 2 (TAPS), TETRA Release 2 (TEDS), Project MESA
Satellite and Over the Horizon Communications	HF Data Link, Connexion By Boeing, IGSAGS, SDLS, Thuraya, Inmarsat, Boeing, Sensis, Iridium, Globalstar
Custom Narrowband VHF	VDL Mode 2, VDL Mode 3, VDL Mode 3 w/SAIC, VDL Mode E, VDL Mode 4, E-TDMA
Custom Wideband	ADL, Flash-OFDM, UAT, Mode-S, B-VHF (MC-CDMA)
Military Communications	Link 16, SINCGARS, EPLRS, HAVEQUICK, JTRS
APC Telephony	Airphone, AirCell, SkyWay

2.3.4 Evaluation of Technologies in Accord with a Concept of Use

As illustrated in figure 2.3-1, the technologies that pass the minimum threshold test (i.e., the best subset of each family) are evaluated in accord with the chosen criteria described in section 2.2. For such evaluation, two areas of information are critically important to describe:

- **Services Offered:** this is a description of the communications services offered by the candidate and is given within the construct of service classifications defined for the Integrated Services Digital Network (ISDN) illustrated in table 2.3-2.
- **Architecture:** this is a description of the reference architecture of the candidate that relates to its physical implementation or functional decomposition, as applicable

The above information is then used to develop a 'Concept of Use' description for each candidate technology. The Concept of Use describes how the candidate is applied to the aeronautical application and consists of two elements:

- **Services Appropriate for Aeronautical Communications :** this description selects which of the services offered by a candidate technology are most applicable to aeronautical communications and describes how these services will be used in the aeronautical environment
- **Integration of the Candidate's Architecture for Aeronautical Communications:** this description discusses how the candidate architecture integrates into existing and future aeronautical communications infrastructure of the service provider and the aircraft

The Concept of Use description then becomes the basis for evaluation of a candidate technology in accord with the chosen evaluation criteria that are described in section 2.2.

Table 2.3-2: ISDN Service Classifications

Bearer Services	Bearer Services are those telecommunications services which provide user information transport between network access points. These services are typified by lower-layer functionality, typically limited to OSI layers 1 through 3. The user may choose any set of high-layer protocols (layers 4-7) but the bearer service will not ascertain compatibility between users at these layers.
Teleservices	Those telecommunications services which provide complete facilities for transfer of user information, including terminal functions. These services are typified by both lower-layer (OSI layers 1 through 3) and higher-layer (OSI layer 4-7) functionality. Teleservices may be built on a named bearer service of the network or may require unique bearer capability which is not separately definable.
Supplemental Services	Those telecommunications services which modify or enhance the capabilities of a bearer service or a teleservice. Supplementary services cannot be offered alone. They must be associated with some other bearer or teleservice. The same supplementary service may be associated with several bearer or teleservices.

As illustrated in the figure 2.3-1 depiction of the pre-screening process, after all of the technologies in the chosen subset of each family are evaluated, comparative and sensitivity analyses are conducted on all candidates chosen from the different families. This process applies weights to the Green, Yellow and Red evaluation scores in order to identify the technologies that may provide sufficient value for further detailed study. This process takes into consideration the ability of a candidate to provide all the desired communications capabilities across all airspace domains (enroute, terminal, surface, oceanic, polar) as well as the ability of a candidate to provide only a subset of capabilities across specific domains. This process and the results are discussed in section 4.

3. Technology Evaluations

3.1 Introduction to Technology Families

Table 3.1-1 lists the technology families and the candidates included within family that are discussed in this section 3. Each family is discussed in a dedicated subsection in the order listed in the table. Additionally, each family is discussed in accord with a uniform general outline as follows:

- 3.X.1 Overview of Technology Family
- 3.X.2 Down Selection of Candidates via Minimum Threshold Test
- 3.X.3 Technology Descriptions: Services and Architecture
- 3.X.4 Concept of Use: Applicable Services and Architecture Integration
- 3.X.5 Evaluation Summary and Scores

Table 3.1-1: Technology Candidates Grouped by Families

Technology Family	Candidate Solutions
Cellular Telephony Derivatives	TDMA (IS-136), CDMA (IS-95A), CDMAone (IS-95B), CDMA2000 1xRTT, W-CDMA, TD-CDMA, CDMA2000 3x, CDMA2000 1xEV, GSM/GPRS/EDGE, TD-SCDMA, DECT
IEEE 802 Derivatives	IEEE 802.11, IEEE 802.15, IEEE 802.16, IEEE 802.20, ETSI HIPERLAN, ETSI HIPERMAN
Public Safety Radio	APCO P-25 Phase 1, APCO P-25 Phase 2, TETRA Release 1, TETRAPOL, IDRA, IDEN, EDACS, APCO P-34, TETRA Release 2 (TAPS), TETRA Release 2 (TEDS), Project MESA
Satellite and Over the Horizon Communications	HF Data Link, Connexion By Boeing, IGSAGS, SDLS, Thuraya, Inmarsat, Boeing, Sensis, Iridium, Globalstar
Custom Narrowband VHF	VDL Mode 2, VDL Mode 3, VDL Mode 3 w/SAIC, VDL Mode E, VDL Mode 4, E-TDMA
Custom Wideband	ADL, Flash-OFDM, UAT, Mode-S, B-VHF (MC-CDMA)
Military Communications	Link 16, SINCGARS, EPLRS, HAVEQUICK, JTRS
APC Telephony	Airphone, AirCell, SkyWay

3.2 Cellular Telephony Derivatives

In this section we will discuss candidate solutions from the cellular telephony technology family. The cellular telephony technology family encompasses all cellular telephony systems from the first generation analog systems to the future fourth generation systems.

3.2.1 Overview of the Family

Cellular telephony systems have undergone a very fast-paced evolution since their inception in the early 1980s. Decades later, we can look back and trace the rapid development of cellular standards and system implementations that have made cellular telephony a mature, technologically advanced and very successful industry. A rapid increase in demand for voice and data services has driven cellular system designers to lead the way in developing innovative solutions to provide new voice and data services and increased user capacity. While this fast-pace of evolution is foreign to the aeronautical environment, cellular telephony systems provide a rich technology base that may provide significant value for future aeronautical communications.

3.2.1.1 Hierarchy of Cell Sizes

Cellular systems consist of a network of radio cells that can provide continuous coverage over the surface of a continental sized land mass. Cells sizes range from a few hundred meters in diameter to many kilometers in diameter. Cells are classified by their size and fall into one of the four levels in the cellular telephony coverage hierarchy as seen in figure 3.2-1. The four major cell classifications, in increasing size, are pico cell, micro cell, macro cell, and global cell.

- Pico cells provide the smallest coverage area. They are typically designed for congested “hot spots” such as hotels, airports, or office buildings and do not exceed a few hundred meters in diameter. The next level in the coverage hierarchy is the micro cell.
- Micro cells are used in less congested areas such as city centers and do not exceed a few kilometers.
- Macro cells are the next level in the coverage hierarchy with coverage areas on the order of tens of kilometers.
- Global cell coverage is served by a satellite to provide coverage to an entire continent, ocean, or group of countries.

A cellular service provider chooses the cell size in inverse proportion to the number of mobile users in a region. Low density rural areas are covered by large macro cells, while dense urban areas are covered by networks of micro and pico cells. Cellular telephony has the most applicability to the aeronautical environment in its ability to support very large macro cells since the current aeronautical communications ground infrastructure is a essentially a lattice of very large macro cells

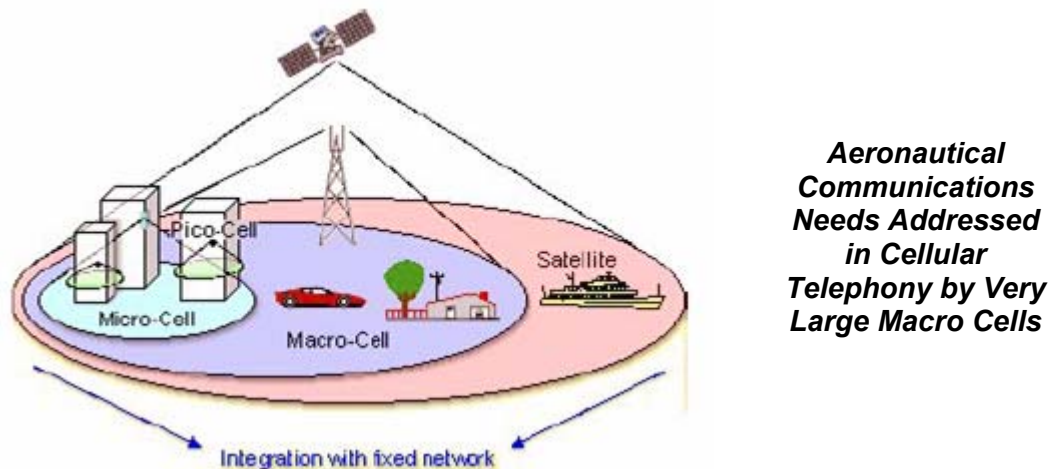


Figure 3.2-1: Cellular Telephone Coverage Hierarchy

3.2.1.2 Technology Evolution

The evolution of cellular technology and services is summarized in figure 3.2-2. Cellular systems are now in their third generation of evolution known as 3G. Before 3G, there was 1G, 2G, and 2.5G. Each cellular generation tends to last about 10 years, but multiple generations typically operate simultaneously over a long transition period. 1G systems first appeared in the early 1980s. 1G systems were analog and offered voice services only. In the early 1990s, 2G systems were deployed. Cellular companies transitioned from analog to digital for 2G systems and began to offer low rate circuit data services and short message services (text messaging). By the late 1990s, there was such a demand for higher data rates and packet data services that cellular companies decided they could not wait for 3G. Instead they made an executive decision to deploy 2.5G systems as an intermediate technology to meet those demands. 3G is the culmination of over two decades of cellular evolution. The rollout of 3G systems began in the early 2000s. 3G systems offer high data rates (up to 2Mbps), internet access, location based services (GPS enabled), and multimedia applications such as streaming video and audio. Finally, 4G systems are in planning and will probably start rolling out after 2010. However, in the competitive cellular environment, earlier rollouts will likely take place prior to a formal standard if there is a business case for it. For example, there are already some systems being put in place as pilot programs that offer services and features anticipated for 4G standards.

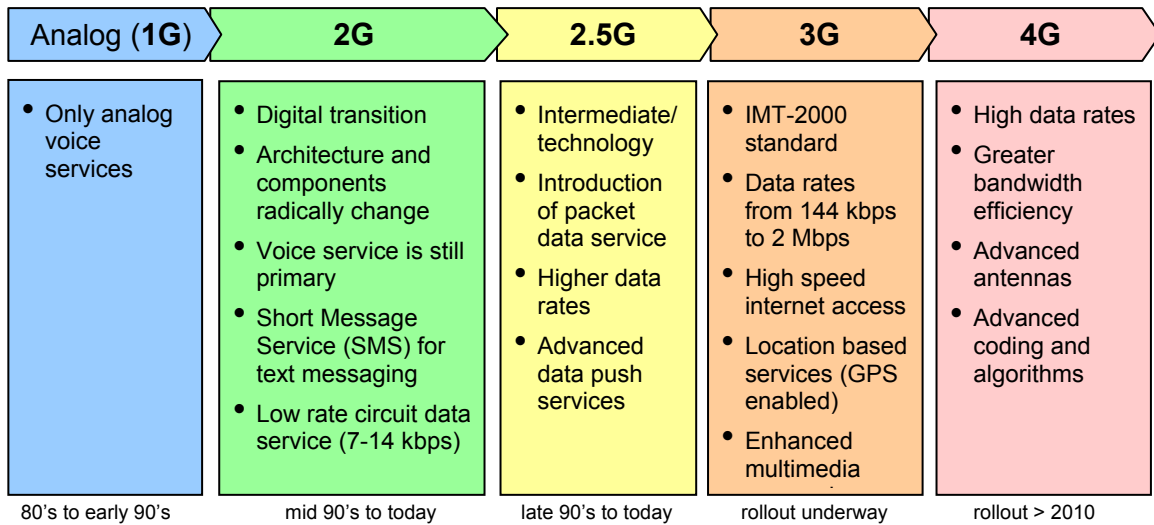


Figure 3.2-2: Evolution of Cellular Services by Generation

3.2.1.3 Cellular Candidate Solutions

Figure 3.2-3 illustrates the major digital cellular standards that have been widely implemented and have potential applicability to aeronautical communications. Although this appears to be a complex picture, all of the standards are encompassed by just two evolutionary threads:

- UTRA European Thread:
 - GSM, with GPRS and EDGE enhancement
 - WCDMA, TD-CDMA, TD-SCDMA: inherits GSM higher protocol layers but are completely redesigns of the lower layers
- CDMA 2000 Thread
 - Qualcomm IS95a/b evolves to CDMA2000 1xRTT
 - Major redesign of 1xRTT above PHY later leads to 1xEV-DO and 1xEV-DV
 - 3x is a multicarrier composite of 1x systems

The standards in the cellular technology family have evolved together, each borrowing techniques from one another. Technologists are optimistic that all of these air interfaces will converge to a single standard for 4G and that that will likely be integrated with standards for wireless LANS.

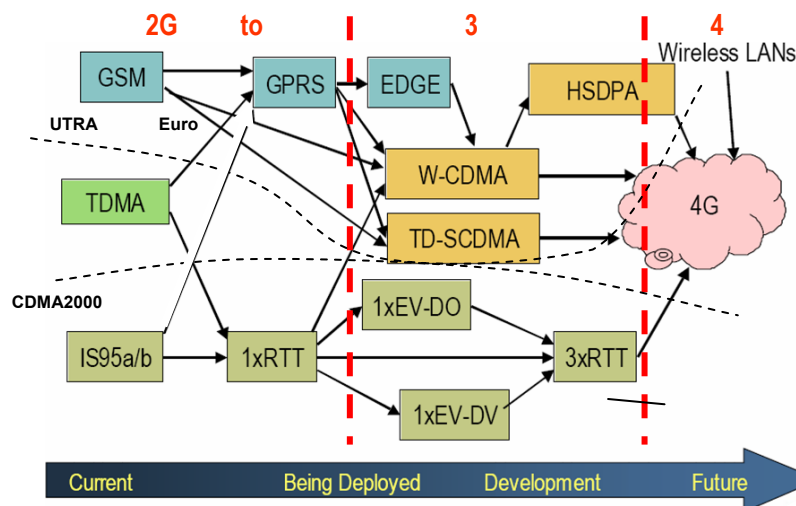


Figure 3.2-3: Candidate Cellular Standards

Each of the above standards in the above figure is briefly described below.

Wideband-CDMA (W-CDMA) is the 3G evolution of the GSM network. W-CDMA is a direct spread, wideband frequency division duplex CDMA standard developed by 3GPP. W-CDMA signals have a bandwidth of 5 MHz. W-CDMA, also referred to as UMTS FDD or UTRA FDD, is proposed as a candidate solution by the ACP. 3GPP is also developing a High-Speed Downlink Packet Access (HSPDA) service that offers higher data rates.

Global System for Mobile Communications (GSM) is the dominant cellular standard in Europe and the most successful cellular system to date. GSM is a frequency division duplex TDMA 2G standard that uses 200 kHz channels. General Packet Radio Service (GPRS) is an extension to GSM that provides a higher data rate packet service. Enhanced Data Rates for GSM Evolution (EDGE) is a technology that gives GSM the capacity to handle services for the third generation of mobile telephony. EDGE provides three times the data capacity of GPRS. Using EDGE, operators can handle three times more subscribers than GPRS; triple their data rate per subscriber, or add extra capacity to their voice communications. EDGE uses the TDMA (Time Division Multiple Access) frame structure, logic channel and 200 kHz carrier bandwidth GSM networks, which allows existing cell plans to remain intact. These technologies have been lumped together as a single candidate solution: GSM/GPRS/EDGE.

Time Division-Code Division Multiple Access (TD-CDMA), also referred to as UTRA TDD, is the time division duplex counterpart to W-CDMA. This technology falls under the IMT-TD radio interface. TD-CDMA uses a combined TDMA and CDMA scheme. This standard is designed to be used in hot spots for dual-mode handsets that support both W-CDMA and TD-CDMA. TD-CDMA is one of the two TDD candidate solutions.

Time Division-Synchronous Code Division Multiple Access (TD-SCDMA) also falls under the IMT-TD classification radio interface. TD-SCDMA is a time division duplex CDMA standard that is similar to TD-CDMA. TD-SCDMA is being developed by the TD-SCDMA Forum for use in China. China has the largest mobile phone market in the world. The TD-SCDMA signal has a 1.6 MHz bandwidth.

CDMA2000 is an entire family of standards that evolved from the CDMAone network. CDMA2000 has four variations: CDMA2000 1x, CDMA2000 1xEV-DO, CDMA2000 1xEV-DV, and CDMA2000 3x. All of the 1x signals have a 1.25 MHz bandwidth. CDMA2000 3x is constructed with multiple CDMA2000 1xEV components, and together occupy 5 MHz of bandwidth. CDMA2000 3x is a multi-carrier, frequency duplex CDMA standard developed by 3GPP2. EV-DO and EV-DV stand for Evolution Data Only and Evolution Data and Voice, respectively. The EV signals are not multi-carrier signals by themselves. CDMA2000 3x will be considered as a separate candidate solution, while both CDMA2000 1xEV-DO and CDMA2000 1xEV-DV will be lumped together as different candidate solution: CDMA2000 1xEV. CDMA2000 1x or CDMA2000 1xRTT is actually considered a 2.5G technology and will also be considered as a different candidate solution. CDMA2000 1x was proposed as a candidate solution by the ACP.

CDMAone, also known as IS-95B, is the 2.5G standard that evolved into CDMA2000. Its 2G predecessor, CDMA IS-95A, was the first CDMA cellular standard. Both IS-95A and IS-95B use 1.25 MHz wideband channels. The CDMAone network provides much higher data rates than the original CDMA.

TDMA or IS-136 is a 2G TDMA cellular system that uses a 30 kHz channel. IS-136 evolved directly from the 1G AMPS system and is sometimes referred to as Digital-AMPS (D-AMPS). It does not fit into either the UTRA European thread or the CDMA2000 thread and has no unique successor. All installed TDMA systems are transitioning to either GSM or to CDMA2000.

One of the original goals for 3G was for all of the air interfaces to converge to a single standard, but this goal clearly was not met. The International Telecommunications Union (ITU) approved the five different air interfaces for 3G, known as IMT-2000, as indicated in table 3.2-1 below.

Table 3.2-1: ITU-Approved 3G Cellular Standards

- IMT-DS (Direct Spread): W-CDMA
- IMT-MC (Multi Carrier): CDMA2000 3x and 1x EV variants
- IMT-SC (Single Carrier): UWC = GSM/GPRS/EDGE
- IMT-FT (Frequency Time): DECT
- IMT-TD (Time Division): TD-CDMA and TD-SCDMA

All but DECT have already been defined. Digital Enhanced Cordless Telecommunications (DECT) is designed for pico cell coverage and provides private branch exchange functionality in office building environments.

3.2.1.4 Key Discriminating Parameters of Cellular Standards

Table 3.2-2 shows some of the key parameters of the different cellular standards. Some of the cellular standards offer only limited range (i.e., cell radius) because of inherent time division aspects of the physical layer. For example, guard times engineered into some standards prohibit the implementation of very large cells (i.e., up to 200 nm) that are used in low traffic enroute airspace environment. The standards shown are either frequency-duplexed (FDD) or time-duplexed (TDD). FDD standards tend to support the larger cell sizes applicable to aeronautical communications. However, they require a pair of frequency bands separated by a large guard band. They transmit and receive on the different frequency bands and thus are not amenable to reengineering to support direct mobile-to-mobile communications required in the aeronautical environment. TDD standards do not support very large cell sizes, but like current aeronautical communications, they require only a single frequency band that is used for both transmit and receive. Thus, it would be easier to reengineer a TDD system to support direct mobile-to-mobile communications. In addition, TDD systems make very efficient use of bandwidth where there is a significant asymmetry between uplink and downlink traffic volume. The table also shows that the standards embody a wide range of signal bandwidth from 200 kHz to 5 MHz. Finally, it is important to point out that cellular standards were designed to support mobile speeds of at most 250 km/h and that the channel and its capacity degrades at such high speeds. However, a GSM extension for the European rail system (GSM-R) supports mobile speeds up to 500 km/h. Clearly, this is still well below the cruise speed of a jet airplane, but it is important to note that all of the cited speeds for the cellular standards are applicable to the non-line-of-sight (NLoS) channel, which imposes more severe constraints than a LoS channel, where there is a clear direct path between ground and aircraft antennas. Accordingly, in a LoS channel, one would expect that much higher speeds could be supported. This has been at least partially demonstrated in field tests with both WCDMA and TD-CDMA that have been conducted by Eurocontrol. In these tests Doppler effects generated by aircraft speeds of up to 400 knots (740.8 km/h) were compensated without any noticeable bit error³. In the TD-CDMA test, the desired range of 25km was achieved via alterations to the timing advance mechanism that enables transmissions from a mobile station to arrive at a base station at the right time (a feature incorporated in the TD-SCDMA standard).

Table 3.2-2: Key Parameters of 3G Cellular Technologies

Standard	Peak Data Rate	Maximum Range	Duplexing Approach	Channel Bandwidth	Maximum Mobile Speed
WCDMA	2 Mbps	No explicit limitations	FDD	2 x 5 MHz	250 km/h
CDMA2000 1xEV	2 Mbps	100 km	FDD	2 x 1.25 MHz	250 km/h
GSM/GPRS/EDGE	400 kbps	35 km	FDD	2 x 200 KHz	250 km/h 500 km/h (rail extension)
TD-CDMA	2 Mbps	30 km	TDD	5 MHz	120 km/h
TD-SCDMA	2 Mbps	40 km	TDD	1.6 MHz	> 120 km/h
DECT	552 kbps	300 m	TDD	1.728 MHz	walking

3.2.2 Selection of Evaluation Candidates via Minimum Threshold Test

Many of the cellular systems are variations of or are closely related to each other. Because of these interrelations of cellular standards it is not necessary to evaluate every single cellular standard. A more efficient approach is to reduce the number of cellular candidates by applying the Minimum Threshold Test process (described in section 2.3.3) to the cellular technology family. Table 3.2-3 lists all of the cellular candidates and gives a rationale for filtering out some and bringing others forward for formal evaluation. The four candidate solutions we have selected to evaluate further are identified in green. Furthermore, because of their similarities, we consider the chosen WCDMA and CDMA2000 1x EV technologies as a single candidate, and that candidate is designated as WCDMA. The primary difference between WCDMA and CDMA2000 1x EV is the smaller channel bandwidth of the CDMA2000 relative to WCDMA. This may be a desirable feature if eventual spectral constraints require a narrower channel mask. Another important difference is the range constraint of CDMA2000. This is due to the length of the common forward link spreading code used by all cell sites. This constraint can be relaxed by a modification to the standard that incorporates a longer spreading code. Furthermore, we chose TD-SCDMA over TD-CDMA because TD-SCDMA eliminates the uplink/downlink interference which affects TD-CDMA by applying “terminal synchronization” techniques (the “S” in TD-SCDMA stands for “synchronization”). Because of this, the TD-SCDMA standard allows full network coverage over macro cells, micro cells, and pico cells. Finally, the GSM/GPRS/EDGE standard was chosen for evaluation because its relatively narrowband 200 kHz channelization may accommodate the spectrum constraints associated with the target band.

Table 3.2-3: Identification and Rationale for Selection of 2G/3G/4G Candidate Solutions

System	Evaluate	Rationale
2G/2.5G Systems		
TDMA (IS-136)	No	Becoming obsolete
CDMA (IS-95A)	No	Superseded by more advanced evolution of this basic technology
CDMAone (IS-95B)	No	Superseded by more advanced evolution of this basic technology
CDMA2000 1xRTT	No	Element of a proposal to ACP; superseded by more advanced evolution (1x EV) of this basic technology
3G Systems		
IMT DS/ WCDMA	Yes	Element of a proposal to ICAO ACP; designed for wide area access and support of large macro cells.
IMT TD/ TD-CDMA	No	Designed primarily for high user density local area access in context of small macro, micro, and pico cells; offers no value over TD-SCDMA, which has a very similar design
IMT MC/ CDMA2000 1x EV	Yes	The 1.25 MHz bandwidth may be more easily accommodated by constraints of available spectrum.
IMT MC/ CDMA2000 3x	No	Provides no added value over the combination of WCDMA and CDMA2000 1x EV
IMT SC/ GSM/GPRS/EDGE	Yes	Most successful cellular communications system to date; additionally, its relatively narrow 200 kHz bandwidth provides a unique value where the spectrum constraints may prohibit the use of wideband signals
IMT FT/ TD-SCDMA	Yes	Of all the time duplex systems, this is the most applicable to the aeronautical environment because it allows for full network coverage over macro cells, micro cells, and pico cells
ITM FT/ DECT	No	Supports only very small cells; offers nothing over TD-SCDMA.
4G Systems		
TBD	No	Still being defined so its parameters are not sufficiently established to evaluate.

3.2.3 Technology Description

The four candidate solutions brought forward from previous section are described in this section in accordance with the Services Provided and Key Features, Functional Architecture, and Air Interface.

3.2.3.1 Services Provided and Key Features

Table 3.2-4 displays the various services supported by the considered 3G cellular systems. Note that the Bearer services supported include both packet and circuit data. Also, the focus of Teleservices in cellular systems has been the standard dialed and E911 calls of wired telephony. However, in the GSM extension for the European rail system (GSM-R), the need for other voice services was noted and standardized. Thus the GSM-R standard supports group calls, broadcast calls and call priority interrupts. These services have not been incorporated by any other cellular standards. However, because of the popularity of a proprietary push-to-talk (PTT) voice service offered by one provider (Nextel), PTT over Cellular (PoC) has become the subject of much standardization and development activity. PoC forms talk groups at the air interface and is a service that is functionally the equal of the current PTT party line service of aeronautical communications.

In general, the evolution of services offered in cellular systems has been from circuit to packet services. 2G systems supported only circuit services, while the 3G cellular systems under consideration support both circuit and packet communications. It is significant to note that packet service has been an emphasis of the 3G rollouts underway, and that the vision for 4G systems is to support packet services exclusively.

This implies that all voice communications (not PoC) will eventually be implemented over a packet bearer and supported by Voice over IP (VoIP). Higher data rates and robust quality of service (QoS) should allow the quality of VoIP to be comparable with the voice quality of circuit-based calls. This transition benefits both cellular companies and subscribers in that it supports voice circuits more economically and with less use of bandwidth. Providing voice via VoIP is bandwidth efficient because packets are not transmitted during periods of silence during a voice call. This equates to a greater user capacity in a given bandwidth and this is an important value in the aeronautical environment.

Table 3.2-4: Cellular Services Supported

Service Type	Services Supported
Bearer Services	<ul style="list-style-type: none"> • Packet Switched Data <ul style="list-style-type: none"> - Point to Point (PTP) Services <ul style="list-style-type: none"> ▪ Connectionless Network Service (PTP-CLNS) ▪ Connection Oriented Network Service (PTP-CONS) - Point to Multipoint (PTM) Services <ul style="list-style-type: none"> ▪ PTM Group Call (PTM-G) ▪ IP Multicast (PTM-M) • Circuit Switched Data
Teleservices	<ul style="list-style-type: none"> • Speech <ul style="list-style-type: none"> - Dialed Call - Emergency (911) - PTT Over Cellular (PoC)—only recently • Speech (GSM-Rail) <ul style="list-style-type: none"> - Group Call - Broadcast - Call Priority Interrupt • Short Message Service (SMS) • Cell Broadcast • Various Data Applications
Supplementary Services	<ul style="list-style-type: none"> • Calling Line Identification (CLI) • Call Waiting • Call Hold • Multiparty (up to 5) • Unstructured Supplementary Service Data (USSD) • Call Forward • Call Barring • Location Based Services

3.2.3.2 Functional Architecture

Figure 3.2-4 below is an example of a 3G cellular system architecture. This particular system architecture diagram is for the GSM/GPRS cellular network, but the basic elements of the architectures for all other 3G cellular systems are comparable. The GSM/GPRS network consists of three subsystems: the Base Station Subsystem (BSS), the Network Subsystem (NSS) that support circuit services, and the GPRS Core network that support packet services. The NSS is a circuit telephone based system that interfaces with the public Switched Telephone Network (PSTN) and using circuit telephony signaling protocols (i.e., SS7). In contrast, the GPRS Core network exists solely to support packet services. Thus, the 2G cellular systems do not embody a Core network. It is also interesting to note that with the evolution of packet services exclusively, 4G cellular systems will have a core packet network, but not NSS circuit network. These three subsystems and elements of these subsystems are described below. The figure also highlights a number of interfaces between the architectural elements using the common taxonomy for cellular standards.

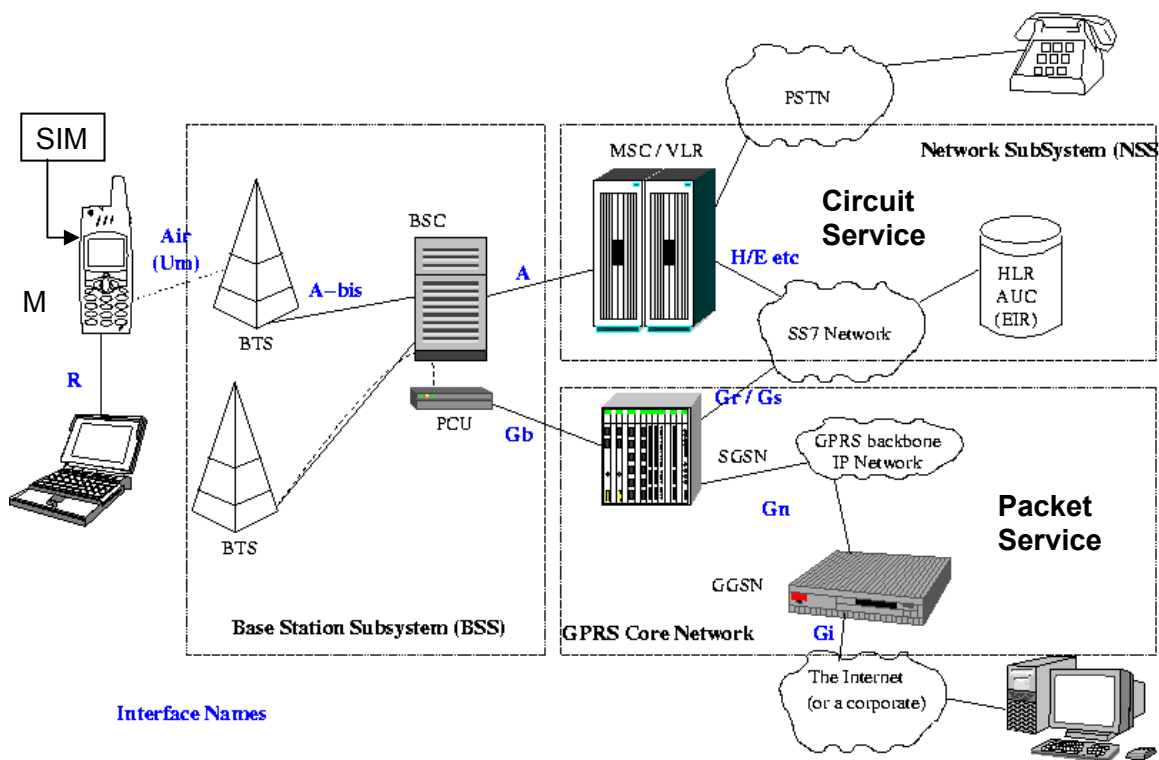


Figure 3.2-4: Example 3G System Architecture (GSM/GPRS)

3.2.3.2.1 Base Station Subsystem

The central component of the BSS is the Base Station Controller (BSC). A typical BSC controls tens or even hundreds of Base Transceiver Stations (BTSs) that transmit to and receive from Mobile Stations (MSs) over the air interface and relay calls to the BSC. A BTS usually has several different transceivers allowing it to serve different frequencies or even different cells. The BSC handles allocation of radio channels, receives measurements from mobile phones and controls handovers from BTS to BTS (except in the case of an inter-MSC handover in which case control is in part the responsibility of the Anchor MSC). BSCs also act as intermediate concentrators of BTS connections to an MSC. The Packet Control Unit (PCU) is a late addition to the GSM standard. It does some of the equivalent tasks of the BSC, but for packet data. The allocation of channels between voice and data is controlled by the BSC, but once a channel is allocated to the PCU, the PCU takes full control over that channel for that transport of packet data. The PCU can be built into the BTS, the BSC or even the SGSN site. In any cellular network

multiple instances of the BSS are present that incorporate thousands of BTSs and hundreds of BSCs and PCUs.

3.2.3.2.2 Network Subsystem (for Circuit Service)

The elements in the NSS provide functionality to support circuit services. These functions include switching, mobility management, authorization and authentication. The Mobile Switching Center (MSC) is a telephone exchange which provides circuit switched services to mobile phones in a certain geographical area. MSC functions include delivering calls to subscribers as they arrive based on information from the Visitor Location Register (VLR); connecting outgoing calls to other mobile subscribers or the PSTN; arranging handovers from BSC to BSC; carrying out handovers from this MSC to another; and supporting supplementary services such as conference calls. The VLR is a registry of subscribers currently in the area. VLR functions include informing the Home Location Register (HLR) that a subscriber has arrived in an area; tracking where the subscriber is within the VLR area (location area) when no call is ongoing; and tracking subscriber on/off state, deleting the subscriber data, and informing the HLR after some time in off state. The HLR is the element where all of the subscribers' data is stored. It contains a large database of subscriber for this HLR's geographical area. A primary functions of the HLR are sending the subscriber data to a VLR where a subscriber has just arrived; sending the subscriber data to an SGSN which requests the information during a routing area update procedure; and removing subscriber data from the VLR where a subscriber has moved from. The Authentication Center (AUC) and the Equipment Identity Register (EIR) are typically collocated with the HLR and provide supplementary authentication services for the user and their equipment.

3.2.3.2.3 The GPRS Core Network (for Packet Service)

The elements of the GPRS Core Network provide functionality to support packet services. These functions include packet data routing, mobility management, session management and transport. The Gateway GPRS Support Node (GGSN) is a router that provides an interface with the Internet or other IP network. It also carries out a mobility management function equivalent to the Home Agent in Mobile IP. The GGSN router de-tunnels user data from GPRS Tunneling Protocol (GTP) and sends out normal user data IP packets. The Serving GPRS Support Node (SGSN) is a router within the core network provides the interface to the PCU. It also carries out a mobility management function equivalent to the Local Agent in Mobile IP. Note that there are typically many instances of the SGSN in a GPRS Core network.

3.2.3.3 Air Interface Description: PHY, MAC, and Network

One function of the air interface in all cellular technologies is to divide up the RF spectrum resources into defined partitions that can be allocated to specific users. All the considered cellular systems use one or more of the following partitioning methods:

- Frequency Division Multiple Access (FDMA): the RF spectrum is divided into distinct channels that are defined by frequency
- Time Division Multiple Access (TDMA): a given RF channel is divided into distinct time slots
- Code Division Multiple Access (CDMA): a given RF channel is divided into distinct code partitions that are each defined by a unique code.

Frequency Duplexed systems (FDD), such as GSM and WCDMA, pre-allocate uplink and downlink channels on separate but paired frequency bands. Time Duplexed systems (TDD), such as TD-SCDMA use and single frequency band that is dynamically allocated via TDMA in accord with the characteristics of uplink and downlink traffic.

3.2.3.3.1 GSM Physical Layer

Figure 3.2-5, illustrating the GSM physical layer, is an example of the way the RF resource is partitioned via a combination of TDMA and FDMA. This shows a pair of 25 MHz bands (separated by 45 MHz) that

are allocated to uplink and downlink in a GSM system. The 25 MHz bands are divided into 124 channels with 200 kHz spacing. This is the FDMA partition of the GSM spectrum. Additionally, each 200 kHz channel is divided into eight (8) subchannels by a period framing structure built from 4.615 ms frames with eight 577 μ s time slots. Each 200 kHz channel and time slot is a distinct resource that can be separately allocated. For circuit service, all the time slots with the same number in every frame are dedicated to the circuit for the duration of the call. By contrast, in packet service, time slots are dynamically allocated as needed to support a given traffic load. This fact illustrates why support voice via a packet service (PoC) is far more efficient than via circuit service. For example, an uplink/downlink pair of 200 kHz GSM channels can support simultaneous circuits from a controller to only 8 pilots. In contrast, PoC time slots are reserved dynamically and independently in uplink and downlink to support the bursty profile of the traffic. Therefore, with PoC, the same uplink/downlink channel pair could support 8 PoC talk groups, in which each may consist of one controller and many aircraft.

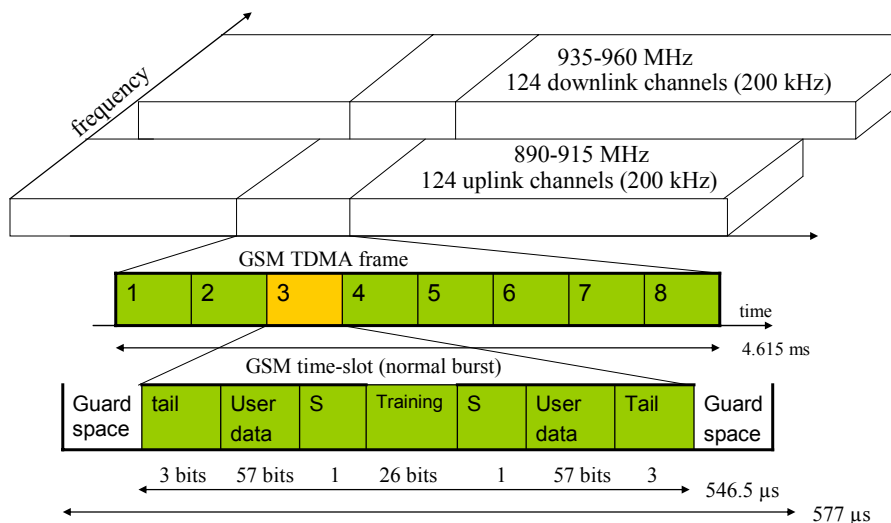


Figure 3.2-5: FDD Air Interface: GSM Physical Layer

3.2.3.3.2 TD-SCDMA Physical Layer

TD-SCDMA partitions the RF resources via a combination of FDMA, TDMA and CDMA. A frequency band set aside for TD-SCDMA is divided into multiple 1.6 MHz channels. Figure 3.2-6 shows the physical structure of the TD-SCDMA air interface and how its code and time division slots are allocated. Each 5 ms TD-SCDMA frame consists of seven 714.3 μ s time slots. CDMA is used to further partition the resource: sixteen orthogonal codes are applied to spread the data. Thus, each time slot consists of 16 separately assignable resources. The uplink and downlink traffic in an each channel share a common 1.6 MHz frequency band, but use it in different time slots that partition the RF resource. The duplex switching point dynamically changes to optimally support asymmetric demand on the uplink and downlink. Support of circuit service requires a code in a time slot reserved for uplink and another for downlink for the call duration. Therefore, an unpaired 1.6 MHz channel can support circuits to at most 50 aircraft. However with packet service (i.e., PoC), the same 1.5 MHz channel could support 50 PoC talk groups, in which each group may consist of one controller and many aircraft. Thus, as with GSM, supporting aeronautical communications with packet service as opposed to circuit service is much more bandwidth efficient. As the only TDD cellular standard under consideration, one interesting feature of TS-SCDMA is that it is more readily adaptable to provide a direct air-air interface since a mobile transmits and receives at the same frequency, just at different times.

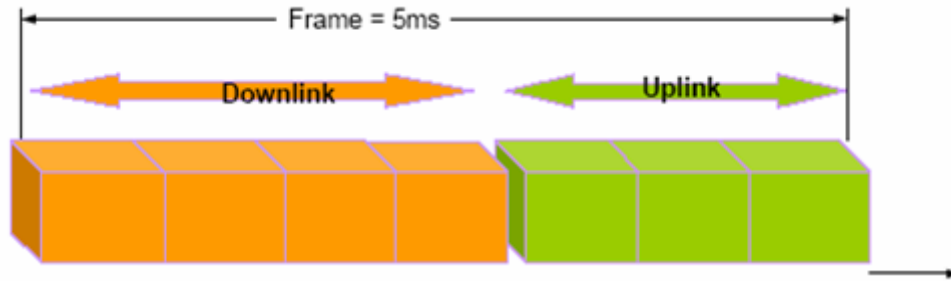


Figure 3.2-6: TDD Air Interface: TD_SCDMA Physical Layer

3.2.3.3.3 *WCDMA and CDMA2000 Physical Layer*

WCDMA and CDMA2000 partition RF resources via a combination of FDMA, CDMA, and TDMA. A frequency band set aside for WCDMA is divided into multiple pairs of 5 MHz channels that are dedicated to uplink and downlink channel, which are separated by a large guard band. With CDMA2000 1x, the channels are 1.25 MHz wide. For both systems, CDMA is the primary mechanism for partitioning the channel. For circuit service, each circuit is assigned a dedicated unique code on both uplink and downlink channels for the duration of the call. The number of unique channel codes used depends on the implemented spreading factor. A high spreading factor creates many partitions (e.g., 128), each with a low data rate. A low spreading factor creates few partitions (e.g., 4), each with a high data rate. With a large spreading factor, a pair of 5 MHz WCDMA channels can support up to 98 aircraft⁴ with dedicated circuits (4.8 kbps). Similarly, a pair of 1.25 MHz CDMA2000 1x channels can support up to 27 aircraft⁵ with dedicated circuits (4.8 kbps). However, as with other cellular systems, providing communications via a packet service is far more efficient. Both WCDMA and CDMA2000 also have TDMA features that support call setup signaling as well as message services. Additionally, in support of packet data services, the TDMA features are much more prominent since bandwidth is allocated by TDMA slot as well as CDMA code. WCDMA is structured with 10 ms frames each of which has fifteen 666.7 μ s time slots. CDMA2000 is similarly structured with frames and time slots. As with the previously described systems, in support of packet service, time slots are dynamically allocated in accord with the traffic load. Other than the differences in bandwidth and capacity, the major difference between WCDMA and CDMA2000 is that the former uses asynchronous cells each with a unique spreading code, while the latter uses synchronous cells that utilize the same spreading code, but with a different time phasing. The CDMA2000 approach makes for rapid signal acquisition, but it does put some strict limitations on the maximum cell size (of 100 km) since each base station is distinguished by the time offset of the spreading code.

3.2.4 *Concept of Use: Application to Aeronautical A/G Communications*

In this concept of use section, the application of cellular communications to aeronautical communications is described, and this provides the basis for subsequent evaluation. This concept of use description involves the following elements:

- Applicable Frequency Band: the band or bands that are appropriate for the implementation of cellular technology for aeronautical communications
- Applicable Airspace: the airspaces in which cellular technology can practically provide aeronautical communications
- Services Used: the cellular services that are best applicable to aeronautical communications
- Architecture Integration: description of how the cellular architecture integrates into the architecture for aeronautical communications.

Each of these is, in turn discussed below.

3.2.4.1 *Applicable Frequency Band*

Cellular technology is best deployed in the DME band (960 to 1024 MHz). There is ample bandwidth to accommodate multiple channels as well as a needed guard band for the frequency duplex cellular systems. The DME frequency is also within the design range for cellular technologies. In the high frequency MLS band (5000 to 5150 MHz), cellular technology has a very unfavorable link budget at large range between omni antennas. Accordingly, this band would not be suitable for enroute or terminal applications. Finally, cellular technology is not suitable for deployment at VHF because of a combination of the transition obstacles (e.g., wideband waveforms and VHF congestion) and the need for a significant guard band (for the frequency duplex systems).

3.2.4.2 *Applicable Airspace Environments*

Cellular technology is applicable in the enroute, terminal, and surface airspace zones where the infrastructure of ground stations exists to support continuous coverage of the NAS. It is not applicable to the oceanic or polar airspace environments. In the high enroute environment, where LoS may be maintained out to 200 nm, there is a potential need for very large cells that can provide communications out that far from a single ground station. This poses a problem for cellular technologies that have a relative hard limit on the maximum supported cell size (see table 3.2-2). Notably, WCDMA has no explicit limitations on cell radius, while CDMA2000 has a maximum cell size of 100 km. This limit is traceable to the design feature that uses a common spreading code from all ground stations with a phase offset large enough to unambiguously distinguish cell transmissions from that of its neighbors. The GSM and TD-SCDMA cellular technologies under consideration have maximum cell sizes of 35 km and 40 km, respectively, making their application to the enroute environment not very practical.

3.2.4.3 *Applicable Cellular Services*

Table 3.2-5 provides a description of three concepts for the application of cellular services to aeronautical communications. Concepts A and B are based on cellular circuit service. In Concept A, a circuit is temporarily set up whenever the Controller and Pilot need to communication via voice or data, and when the transaction is complete, the circuit is terminated. In Concept B, a persistent circuit is maintained to every aircraft in a sector. Concept C is based on cellular packet service. In this concept, all voice and data is conveyed over packet communications. Of these concepts, Concept B is clearly the most consumptive of spectrum. Concept A uses spectrum more efficiently, but the required setup time for a circuit is not compatible with emergency or tactical communications. Concept C appears to be a good compromise in that is both spectrum efficient, and avoids the potentially long setup time for circuit service.

Table 3.2-5: Cellular Service Concepts for Aeronautical Communications

Concept A: Circuit Service: Transient	Concept B: Circuit Service: Persistent	Concept C: Packet Service/(PoC)
<ul style="list-style-type: none"> • Temporary circuit is established (via a phone call) for duration of each transaction between a Controller and a Pilot in a sector • Only one circuit is used by a Controller at any point in time 	<ul style="list-style-type: none"> • Persistent circuit is established between a Controller and each Pilot in the associated sector (via phone call) • Circuit is transferred to a new Controller at a sector boundary and is never terminated • Many simultaneous circuits (equal to the number of aircraft in a sector) are used by a Controller at any point in time 	<ul style="list-style-type: none"> • Packet Service supports all data communications • PTT over Cellular (PoC) service is used to create and maintain a group voice conference for all aircraft in the sector and supports access via PTT

Table 3.2-6 provides a mapping that shows how these three cellular service concepts could provide the services needed in aeronautical communications. It addresses the three service concepts introduced above and their ability to support the capabilities applicable for aeronautical communications. Since base station

infrastructure is inherent to cellular technologies, direct Air-Air communications is not supported by these or any other concept. Packet Service (i.e., PoC) appears to be best matched since it efficiently supports Group Conferences and all broadcast communications. Persistent Circuit Service requires continuous transmission to and from all supported aircraft, which is spectrally inefficient. In addition, its support of Group Conference and Data Broadcast requires a bridge for all the circuits. If this bridge is done at a control site, the telecommunication lines between radio and control sites will increase many fold. Alternatively, bridging the circuits at the radio sites will not require an increase in lines, but will require voice switch functionality at the radio sites, which is likely to have a large integration complexity and cost impact. Persistent circuit service also does not meet the requirements of broadcast voice since a circuit must be established just to join in the broadcast. Finally, while Transient Circuit Service is spectrally more efficient than Persistent Circuit Service, it can support only the point-to-point voice and data services and none of the broadcast or conference services. Furthermore, with this service, each transaction experiences the delays required for circuit setup. The conclusion of this discussion is that cellular packet services provide the best and most efficient support to aeronautical communications, and because of this, this is the concept we used as the basis for evaluation of cellular technologies.

Table 3.2-6: Ability of Cellular to Meet Communications Needs.

Cellular Service Concepts	Aeronautical Communications Needs						
	Group Voice Conference	A/G and G/A Addressed Voice	A/A Voice (direct)	Broadcast Voice	A/G and G/A Addressed Data	G/A Broadcast Data	A/A Data (direct)
A. Transient Circuit Service	No	✓	No	No	✓	No	No
B. Persistent Circuit Service	✓*	✓	No	No	✓	✓*	No
C. Packet Service (e.g., PoC)	✓	✓	No	✓	✓	✓	No

3.2.4.3.1 Architecture Integration—Service Provider Infrastructure

Figure 3.2-7 illustrates a notional mapping of 3G architectural elements into the NAS infrastructure. It shows that the mobile functionality maps to the avionics. This includes the Subscriber Identity Module (SIM) or smart card that is used for authentication of the mobile user. The cellular BTS equipment maps to the NAS radio sites. All of the other elements of the cellular architecture map to the control sites or other centralized facility.

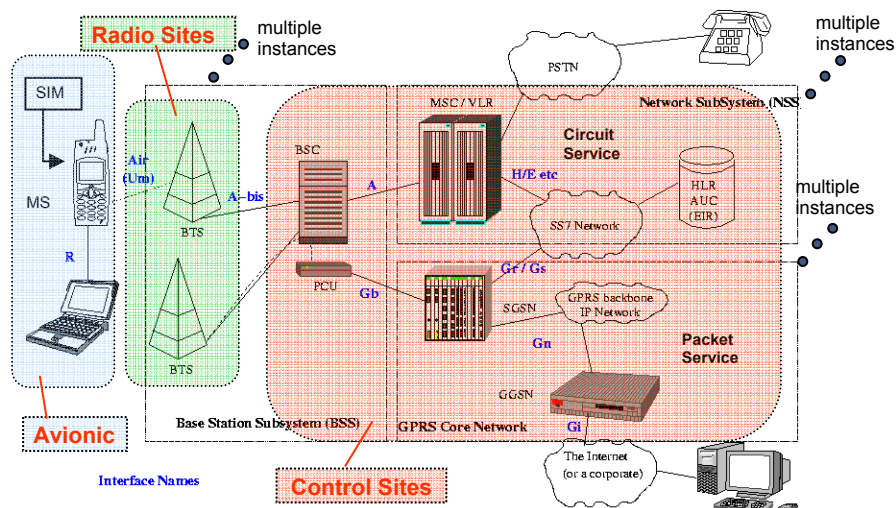


Figure 3.2-7: Notional Integration of 3G Elements into Infrastructure

Figure 3.2-8 gives a bit more detail on how the cellular architectural elements may map to existing elements of the NAS control sites. The SSGN router provides the local access point for data service to aircraft so that should support a direct interface to the controller position and automation data. The MSC that does the circuit switching clearly must integrate with or replace existing voice switches. However, for PoC, which is based on packet service, the voice switch would interface or be integrated with the SSGN. The HLR/AUC/EIR provides authentication services and so tends to provide functions that are envisioned for the Context Manager and NAS Automation systems. Finally, the GGSN router would provide the gateway to the ATN. At this point, the GGSN would encapsulate all of the ATN data within IP packets that would be tunneled from this point to the avionics where it would be stripped back to ATN packets.

It should be clear from this discussion that cellular technology provides a complex set of functions and equipment that have a potentially very wide impact on the NAS infrastructure. Because of this, there is a natural temptation to try to disassemble the architecture and use a chosen subset of elements. While this is not impossible, it must be emphasized that these standards and their interfaces are complex and that one should not underestimate the amount of engineering required to customize a cellular implementation. Disassembling services and/or architectures of these very complex standards will likely entail great costs and thereby forfeit any advantage over a custom solution. A reengineered solution requires large upfront development and ongoing maintenance costs. Reengineered solutions also forfeit opportunity for low-cost by leveraging COTS chips and/or equipment. However, proponents with a willingness to invest in reengineering a 3G system would claim that if there was a will, a system could be developed in a few years. In this vein, Eurocontrol conducted flight trials that have shown cellular air-interface operation at both VHF and MLS frequencies. Nevertheless, for evaluation purposes, we have assumed that services and architecture elements of this COTS technology should be used as they are currently defined or evolving to under the standard with only minor modifications (e.g., to accommodate shifting to an aeronautical spectral band and to accommodate the large Doppler shift for aeronautical communications).

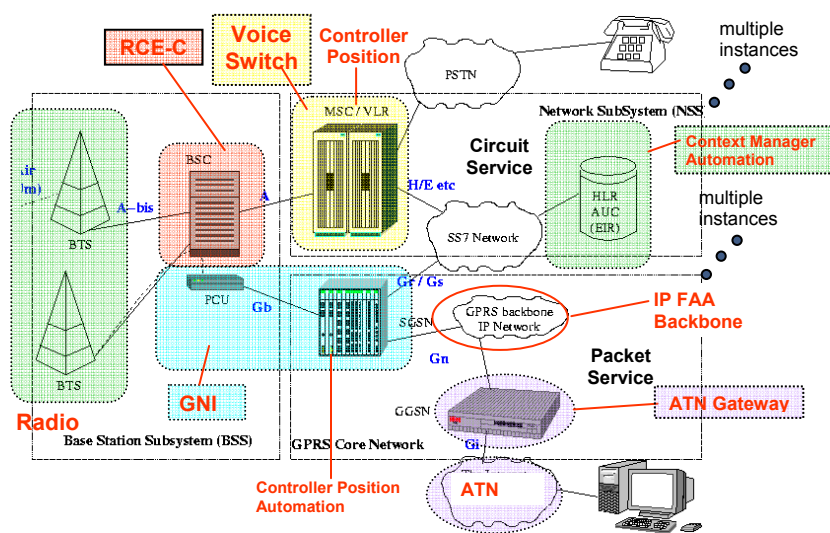


Figure 3.2-8: Notional Integration of 3G Elements into Infrastructure

3.2.4.3.2 Architecture Integration—Avionics

Figure 3.2-9 illustrates a notional integration of 3G cellular technology with aircraft avionics. The elements in green indicate the equipment that would be required for A/G communications via cellular technology. Some other technology (in gray) is required to support direct air-air communications.

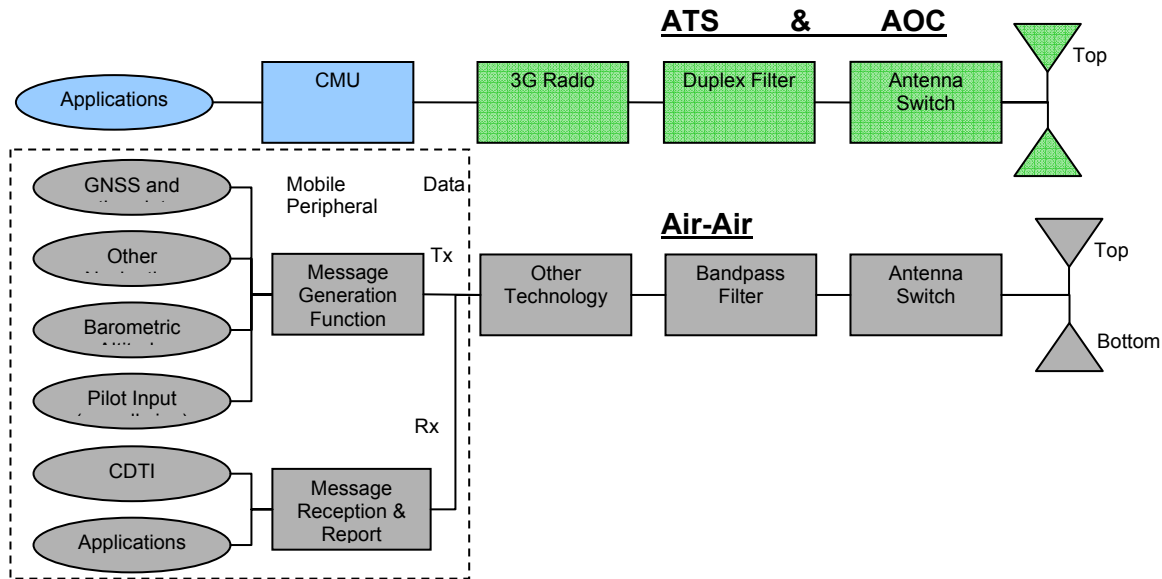


Figure 3.2-9: Notional Integration of 3G Elements into Avionics

3.2.4.3.3 Architecture Integration—Channel Allocation

As previously mentioned, the best available spectrum for cellular technology is in the DME band (960 to 1024 MHz). Deployment in this band allows for multiple duplex 5 or 1.25 MHz channels to be defined. Coverage of airspace may be used in a number of ways. Since all but GSM are single frequency systems, in these systems the same frequency is used in adjacent cells. Thus, one could define a single channel and build a ground station infrastructure to cover all airspace with a single channel or channel pair. Another method might be to dedicate channels allocated to airspace tiers (e.g., channel for ultra-high en-route; for high en-route; surface, ...). A notional frequency plan supporting this is illustrated in figure 3.2-10.

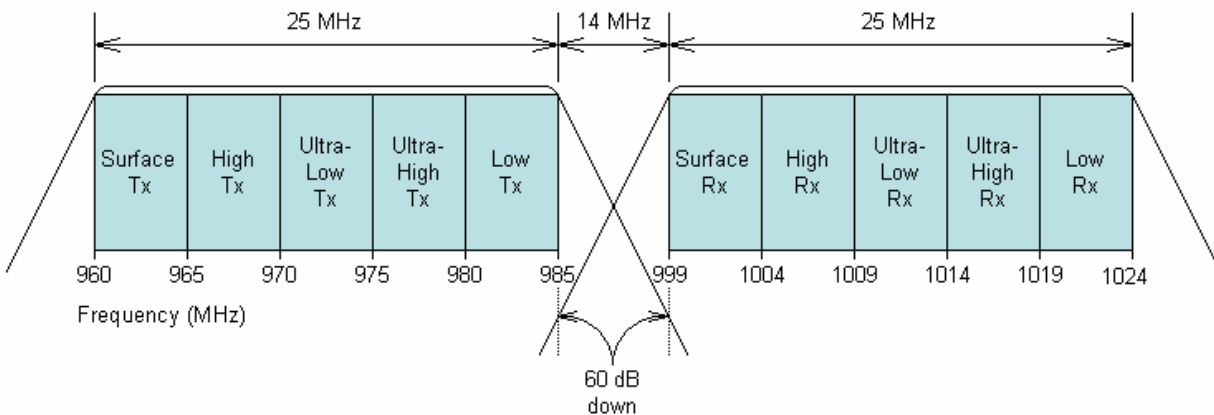


Figure 3.2-10-1: Notional Allocation of Channels in 960 to 1024 MHz band

3.2.5 Evaluation Summary and Scores

This section provides evaluation scores and rationale for GSM, TD-SCDMA, and the WCDMA/CDMA2000 alternatives. The WCDMA and CDMA2000 were evaluated as a single option since that is the way it has been proposed to the ICAO ACP to Eurocontrol, where CDMA2000 1x is a backup to WCDMA if spectrum constraints do not allow the assignment of 5 MHz channels.

Table 3.2-7 provides the scoring summary for GSM. The rationale for the assigned scores is provided in table 3.2-8.

Table 3.2-7: GSM Evaluation Worksheet

	Criteria	Surface	Terminal	En Route	Oceanic	Polar
Voice Needs	1					
Pilot-Controller Talk Group	1A1					
Pilot-Controller Selective Addressing	1A2					
Direct Pilot-Pilot	1A3					
Broadcast capability	1A4					
Capacity provided	1B1					
Address space	1B3					
Aircraft mobility management	1C1					
Latency	1C2					
Basic Data Needs	2					
A/G and G/A Addressed Data Transport	2A1					
Ground-to-Air Broadcast Data Transport	2A2					
Aggregate Data Rate	2B1					
Number of Users	2B2					
Uplink and Downlink Priority Levels / QoS	2C1					
Latency	2C2					
Enhanced Data	3					
ADS-B	3A1					
Pilot-Pilot Data Transport	3A2					
Aggregate Data Rate	3B1					
Technology Readiness Level	4					
Standardization Status	5					
Certifiability	6					
Ground Infrastructure Cost	7					
Cost to Aircraft	8					
Spectrum Protection	10					
Security	11					
Transition	12					

Table 3.2-8: GSM Scoring Rationale

Element	Score	Rationale
Pilot-Controller Talk Group	Green (S, T) Red (E, O, P)	Can be supported natively in surface and terminal areas via PoC service under development for 3G systems; may also be satisfied by GSM-Rail extensions; enroute is judged to be red because of the 35 km maximum cell size for GSM.
Pilot-Controller Selective Addressing	Green (S, T) Red (E, O, P)	Supports natively in terminal and surface areas; enroute is judged to be red because of the 35 km maximum cell size for GSM.
Direct Pilot-Pilot	Yellow (S, T) Red (E, O, P)	Supports via re-broadcast by ground station in surface and terminal airspaces
Broadcast capability	Green (S, T) Red (E, O, P)	Can be supported natively in surface and terminal areas via PoC service under development for 3G systems; may also be satisfied by GSM-Rail extensions
Capacity provided	Green (all domains)	GSM in the DME band creates up to 8 channels for each pair of 200 kHz of allocated bandwidth. Thus, 50 MHz of spectrum would support 1000 new assignable voice channels; note that in cellular installations, GSM channels may be assigned with a reuse factor of 7. Adjacent cells cannot reuse the same frequencies for GSM. Low CCIR provided by modulation (~5 dB) is much lower than that for DSB-AM, making reuse factor more efficient.
Address space	Green (all domains)	PoC should support over 200 mobiles in a talk group.
Aircraft mobility management	Green (S, T) Red (E, O, P)	GSM provides mobility management automatically
Latency	Yellow (all domains)	Connect time will be fast if permanent circuit service is used; group conferences via PoC or GSM-Rail may involve slightly longer latency and connect times
A/G and G/A Addressed Data Transport	Green (S, T) Red (E, O, P)	GSM is an IP network; IP could just be a tunnel for ATN packets.
Ground-to-Air Broadcast Data Transport	Green (S, T) Red (E, O, P)	GSM supports multicast.
Aggregate Data Rate	Green (all domains)	Up to about 384 kbps peak data rate is supported by a single GSM/GPRS/EDGE channel (well above 31.5 kbps)
Number of Users	Green (all domains)	Packet service could be simultaneously supplied to over 200 users on a single GSM channel.
Uplink and Downlink Priority Levels/QoS	Green (all domains)	Packet service supports QoS; the MAC function incorporates a priority reservation protocol.
Latency	Green (all domains)	Packet service should be fast and so is consistent with < 4.5 seconds end-to-end delay.
ADS-B	Red (all domains)	Cannot support since this is an FDD system with no direct mobile-mobile connection.
Pilot-Pilot Data Transport	Yellow (S, T) Red (E, O, P)	Supports air-air data via an intermediary in S and T airspaces
Aggregate Data Rate	Yellow (all domains)	Up to about 384 kbps peak data rate is supported by a single GSM/GPRS/EDGE channel (above 280 kbps but below 2 Mbps)
Technology Readiness Level	Yellow	GSM is mature, but its use in an aeronautical environment has not been demonstrated.
Standardization Status	Yellow	GSM 3G is a mature commercial standard.
Certiability	Red	GSM is not designed and developed to a safety standard.
Ground Infrastructure Cost	Red	Max cell radius of 40 km (determined by TDD) requires many more ground stations to cover en-route sectors; plus new 1 GHz antennas, duplexers, and new radios.
Cost to Aircraft	Green	Cost estimate is comparable to VDL 3.
Spectrum Protection	Yellow	GSM 3G would be deployed in the DME band.
Security	Green	GSM provides authentication and integrity.
Transition	Yellow	Control site infrastructure and core network need to be essentially complete before service can be offered.

Table 3.2-9 provides the scoring summary for TD-SCDMA. The rationale for the assigned scores is provided in table 3.2-10.

Table 3.2-9: TD-SCDMA Evaluation Worksheet

	Criteria	Surface	Terminal	En Route	Oceanic	Polar
Voice Needs	1					
Pilot-Controller Talk Group	1A1					
Pilot-Controller Selective Addressing	1A2					
Direct Pilot-Pilot	1A3					
Broadcast capability	1A4					
Capacity provided	1B1					
Address space	1B3					
Aircraft mobility management	1C1					
Latency	1C2					
Basic Data Needs	2					
A/G and G/A Addressed Data Transport	2A1					
Ground-to-Air Broadcast Data Transport	2A2					
Aggregate Data Rate	2B1					
Number of Users	2B2					
Uplink and Downlink Priority Levels / QoS	2C1					
Latency	2C2					
Enhanced Data	3					
ADS-B	3A1					
Pilot-Pilot Data Transport	3A2					
Aggregate Data Rate	3B1					
Technology Readiness Level	4					
Standardization Status	5					
Certiability	6					
Ground Infrastructure Cost	7					
Cost to Aircraft	8					
Spectrum Protection	10					
Security	11					
Transition	12					

Table 3.2-10: TD-SCDMA Scoring Rationale

Element	Score	Rationale
Pilot-Controller Talk Group	Green (S, T) Red (E, O, P)	Can be supported natively via PoC service under development for 3G systems; enroute is judged to be red because of the 40 km maximum cell size for TD-SCDMA
Pilot-Controller Selective Addressing	Green (S, T) Red (E, O, P)	Supports natively in terminal and surface areas; enroute is judged to be red because of the 40 km maximum cell size for TD-SCDMA
Direct Pilot-Pilot	Yellow (S, T) Red (E, O, P)	Supports via re-broadcast by ground station
Broadcast capability	Green (S, T) Red (E, O, P)	Can be supported natively via PoC service under development for 3G systems; enroute is judged to be red because of the 40 km maximum cell size for TD-SCDMA
Capacity provided	Green (all domains)	A 1.6 MHz TDD band, could support on the order of 50 voice channels; thus 50 MHz of spectrum will supply on the order of 1500 assignable channels; note that in CDMA cellular installation, these channels are assigned with a reuse factor of 1. This means adjacent cells can reuse the same spectrum with a different set of codes. In non-CDMA systems, such as GSM, this is not possible. Low CCIR provided by modulation (~5 dB) is much lower than that for DSB-AM, making reuse factor more efficient.
Address space	Green (all domains)	PoC service supports very large talk groups.
Aircraft mobility management	Green (S, T) Red (E, O, P)	TD-SCDMA provides mobility management automatically
Latency	Yellow (all domains)	Connect time will be low if permanent circuit service is used; group conferences via PoC may involve some longer latency and connect times.
A/G and G/A Addressed Data Transport	Green (S, T) Red (E, O, P)	IP network; IP could just be a tunnel for ATN packets.
Ground-to-Air Broadcast Data Transport	Green (S, T) Red (E, O, P)	IP multicast on top of layer 2 broadcast.
Aggregate Data Rate	Green (all domains)	Up to 2 Mbps peak data rate is supported by a single channel in a TD-SCDMA carrier (well above 31.5 kbps)
Number of Users	Green (all domains)	Packet service could be simultaneously supplied to over 200 users on a single TD-SCDMA channel.
Uplink and Downlink Priority Levels/QoS	Green (all domains)	Packet service supports QoS; the MAC function incorporates a priority reservation protocol.
Latency	Green (all domains)	Packet service should be fast and so is consistent with < 4.5 seconds end-to-end delay.
ADS-B	Red (all domains)	Direct mobile-mobile connection is not supported.
Pilot-Pilot Data Transport	Yellow (S, T) Red (E, O, P)	Supports air-air data via an intermediary in surface and terminal airspaces
Aggregate Data Rate	Green (all domains)	Up to 2 Mbps peak data rate is supported by a single channel in a TD-SCDMA carrier
Technology Readiness Level	Yellow	While flight tests of individual circuits have been done, a specific architecture that details the frequency plan and how a group conference is supported and has not been proposed.
Standardization Status	Yellow	TD-SCDMA is a mature commercial standard.
Certifiability	Red	TD-SCDMA is not designed and developed to a safety standard.
Ground Infrastructure Cost	Red	Max cell radius of 40 km requires more ground stations to cover en route sectors; much new control site infrastructure as well as new 1 GHz antennas, duplexers, and new radios.
Cost to Aircraft	Green	Cost estimate is comparable to VDL 3.
Spectrum Protection	Yellow	TD-SCDMA would be deployed in the DME band.
Security	Green	TD-SCDMA provides authentication and integrity.
Transition	Yellow	Control site infrastructure and core network need to be essentially complete before service can be offered.

Table 3.2-11 provides the scoring summary for W-CDMA/CDMA2000. The rationale for the assigned scores is provided in table 3.2-12.

Table 3.2-11: W-CDMA Evaluation Worksheet

	Criteria	Surface	Terminal	En Route	Oceanic	Polar
Voice Needs	1					
Pilot-Controller Talk Group	1A1					
Pilot-Controller Selective Addressing	1A2					
Direct Pilot-Pilot	1A3					
Broadcast capability	1A4					
Capacity provided	1B1					
Address space	1B3					
Aircraft mobility management	1C1					
Latency	1C2					
Basic Data Needs	2					
A/G and G/A Addressed Data Transport	2A1					
Ground-to-Air Broadcast Data Transport	2A2					
Aggregate Data Rate	2B1					
Number of Users	2B2					
Uplink and Downlink Priority Levels / QoS	2C1					
Latency	2C2					
Enhanced Data	3					
ADS-B	3A1					
Pilot-Pilot Data Transport	3A2					
Aggregate Data Rate	3B1					
Technology Readiness Level	4					
Standardization Status	5					
Certiability	6					
Ground Infrastructure Cost	7					
Cost to Aircraft	8					
Spectrum Protection	10					
Security	11					
Transition	12					

Table 3.2-12: W-CDMA Scoring Rationale

Element	Score	Rationale
Pilot-Controller Talk Group	Green (S, T, E) Red (O and P)	Can be supported natively in surface, terminal and enroute areas via PoC service under development for 3G systems
Pilot-Controller Selective Addressing	Green (S, T, E) Red (O and P)	Supports natively in S, T and E
Direct Pilot-Pilot	Yellow (S, T, E) Red (O, P)	Supports via re-broadcast by ground station
Broadcast capability	Green (S, T, E) Red (O and P)	May be supported via PoC service under development for 3G systems
Capacity provided	Green (all domains)	A pair of 5 MHz channels could support on the order of 100 voice channels; thus 50 MHz of spectrum will supply 500 assignable voice channels; while this is not double the current 760 channels for DSB-VHF, because it is a CDMA waveform, these channels can be assigned with a frequency reuse factor of 1 (vs. 7 for a typical FDMA system). It is thus concluded to achieve a notional doubling because adjacent cells can reuse the same frequencies with a different set of codes. Low CCIR provided by modulation (~5 dB) is much lower than that for DSB-AM, making reuse factor more efficient.
Address space	Green (all domains)	PoC should support over 200 mobiles in a talk group.
Aircraft mobility management	Green (S, T, E) Red (O and P)	WCDMA provides mobility management automatically.
Latency	Yellow (all domains)	Time to connect will be fast if permanent circuit service is used; group conferences via PoC may involve some longer latency and connect times.
A/G and G/A Addressed Data Transport	Green (S, T, E) Red (O and P)	IP network; IP could just be a tunnel for ATN packets.
Ground-to-Air Broadcast Data Transport	Green (S, T, E) Red (O and P)	IP multicast on top of layer 2 broadcast.
Aggregate Data Rate	Green (all domains)	Up to 2 Mbps peak data rate is supported by a single channel in a WCDMA carrier (well above 31.5 kbps)
Number of Users	Green (all domains)	Packet service could be simultaneously supplied to over 200 users on a single WCDMA channel.
Uplink and Downlink Priority Levels/QoS	Green (all domains)	Packet service supports QoS; the MAC function incorporates a priority reservation protocol.
Latency	Green (all domains)	Packet service should be fast and so is consistent with < 4.5 seconds end-to-end delay.
ADS-B	Red (all domains)	Cannot support since this is an FDD system with no direct mobile-mobile connection.
Pilot-Pilot Data Transport	Yellow (S, T, E) Red (O, P)	Supports air-air data via an intermediary in S, T and E airspaces
Aggregate Data Rate	Green (all domains)	Up to 2 Mbps peak data rate is supported by a single channel in a WCDMA carrier
Technology Readiness Level	Yellow	While flight tests of individual circuits have been done, a specific architecture that details the frequency plan and how a group conference is supported has not been proposed.
Standardization Status	Yellow	W-CDMA is a mature commercial standard.
Certifiability	Red	W-CDMA is not designed and developed to a safety standard.
Ground Infrastructure Cost	Red	Much new control site infrastructure as well as new 1 GHz antennas, duplexers, and new radios at remote sites.
Cost to Aircraft	Green	Cost estimate is comparable to VDL 3.
Spectrum Protection	Yellow	W-CDMA would be deployed in the DME band.
Security	Green	W-CDMA provides authentication and integrity.
Transition	Yellow	Control site infrastructure and core network need to be essentially complete before services can be offered.

In summary, cellular telephony standards offer a wealth of capabilities and underlying technology that could be applied to aeronautical communications. There many obstacles to this application, however. With respect to technical performance, extensive work needs to be done to provide a high level of assurance that aeronautical applications, which are well outside the 3G design envelopes for range and Doppler, can be reliably served. A mature and complete concept of use needs to be articulated by proponents and used to demonstrate its full utility and compatibility for aeronautical communications.

With respect to infrastructure cost, insertion of 3G technology could drive changes to much of the A/G infrastructure (e.g., voice switches, automation, antennas, radios, etc.) and prove to be very costly and difficult to manage. With respect to certification, 3G systems are among the most complex and feature-rich communications systems. One can anticipate numerous certification obstacles, some of which may not be solved without significant standards modification.

3.3 IEEE 802 Derivatives

This section addresses the family wireless network standards. There are a variety of wireless standards in this family, including IEEE 802.11, 802.15, 802.16 and 802.20, as well as their European counterparts, ETSI HIPERLAN, HIPERLAN, ETSI HIPERMAN. In this report, this body of wireless standards will be referred to as the 802.xx family.

3.3.1 Overview of the Family

In the world of wireless networks there is a defined hierarchy of network sizes, similar to cell sizes in the world of cellular communications. In increasing order of network size the hierarchy is as follows:

- **Personal Area Network (PAN)**—A PAN typically operates within about 30 feet and is focused on interconnecting devices centered on an individual person's workspace, such as laptops, PDAs, and cell phones.
- **Local Area Network (LAN)**—A LAN operates within 300 yards and is well-suited for use within enterprises, such as an office building floor or even a small office building. The range is enough to provide reliable service to a large number of users, yet narrow enough to reasonably limit access outsiders.
- **Metropolitan Area Networks (MAN)**—A MAN typically operates within an area between 5 and 50 km in diameter. MANs may be as small as a group of buildings or as large as an entire city.
- **Wide Area Network (WAN)**—A WAN typically operates over a large region that incorporates one or more cities and there extended suburbs.

Both the IEEE 802 family and the ETSI family include standards for each level in the wireless network hierarchy. Figure 3.3-1 identifies the comparable standards for both standardization groups for each level in the hierarchy.

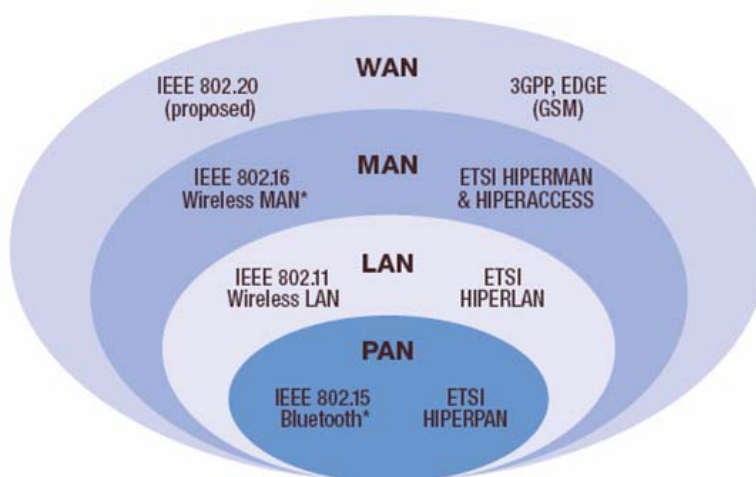


Figure 3.3-1: IEEE and ETSI Wireless Network Standards

Rather than describe each of these standards individually, it makes more sense to describe them by their placement in the hierarchy since standards in the same level are so similar. The discussion will focus on the IEEE standard, rather than the ETSI version because many of the ETSI versions use the IEEE standard as a baseline and describing both in detail would be redundant.

IEEE 802.15 and ETSI HIPERPAN—these are an evolving set of standards that used a variety of modulation and access techniques. Because of their limited range, they are not selected for evaluation. Thus in the interest of brevity, they are not discussed further.

IEEE 802.11 and ETSI HIPERLAN—802.11 is set of evolving standards for LANs. Figure 3.3-2, below, shows how these standards have evolved over time. The original 802.11 standard supports data rates up to 2 Mbps. The most successful of the 802.11 standards are 802.11 (a), (b), and (g). These three standards all incorporate various changes to the physical layer. All the 802.11 standards are defined for the Industrial, Scientific, and Medical (ISM) spectrum band, with the exception of 802.11(a), which is defined over the Unlicensed National Information Infrastructure (UNNI) band. 802.11(g) has recently become the dominant standard under 802.11, with supported data rates up to 54 Mbps. The 802.11 set of standards is still evolving, introducing upgraded features and performance in key areas such as security and QoS. The ETSI counterpart to 802.11, ETSI HIPERLAN, most closely relates to 802.11(a).

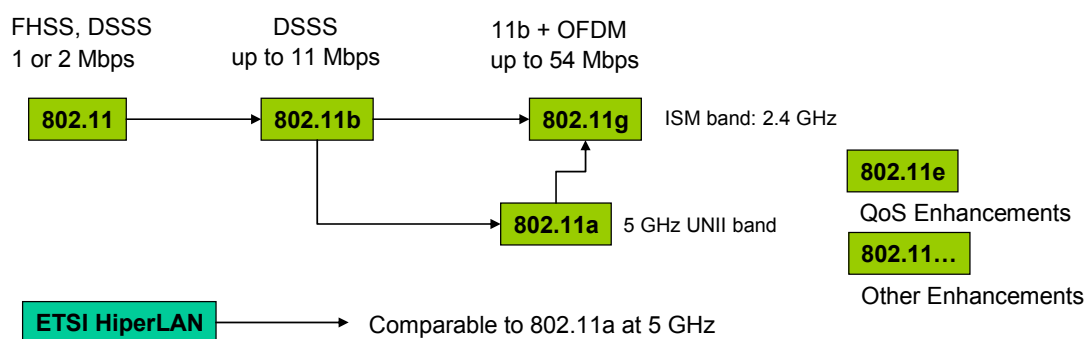


Figure 3.3-2: Evolution of 802.11 Standards

IEEE 802.16, ETSI HIPERMAN, and IEEE 802.20—802.16 is a set of evolving standards for MANs. Figure 3.3-3, below, shows how these standards evolved over time. The original 802.16 standard supports data rates up to 70 Mbps in LoS conditions and operates in the 10-66 GHz band. 802.16(a) shifted down to the 2-11 GHz band and provides data rates up to 70 Mbps in Non-LoS conditions. 802.16(e) supports data rates up to 30 Mbps, but as a trade-off it incorporates service provision to mobile platforms. The ETSI counterpart to 802.16, ETSI HIPERMAN, is analogous to 802.16(a) at 2-11 GHz. HIPERMAN is less mature than 802.16, and it has in fact chosen the 802.16 as its initial baseline. For provision of WAN coverage, the IEEE has constituted an 802.20 standards activity. The 802.20 standard is being developed for frequencies less than 3.5 GHz, will offer data rates up to 2 Mbps and will support higher mobile platform speeds than 802.16(e). However, 802.20 is at a very early stage of development (requirements definition) so that it is clear that 802.16e systems will be fielded and provide mobility years before 802.20 systems are put in place. Accordingly, a likely scenario is that 802.16 will evolve to incorporate 802.20 that are vital to the mobile communications market.

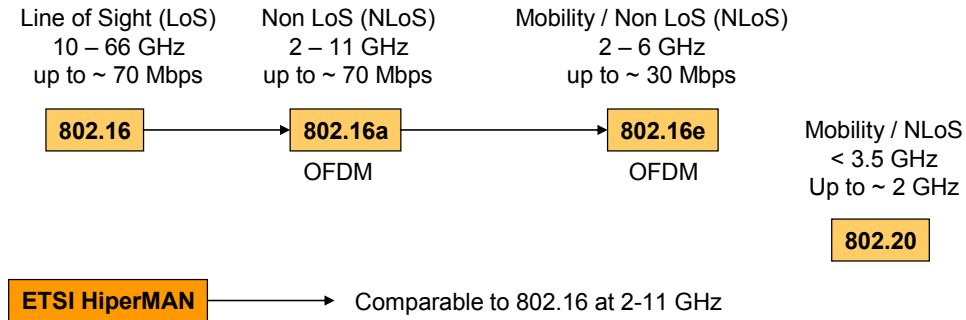


Figure 3.3-3: Evolution of 802.16 Standards

Key Discriminating Parameters of Wireless Network Standards

Table 3.3-1 displays some of the key parameters associated of the different wireless network standards. Some of the wireless network standards are constrained because they offer limited coverage range, support only a small number of users, or support low-speed mobility.

Table 3.3-1: Key Parameters of 802.xx Family of Standards

Standard	Peak Data Rate	Maximum Range	Signal Bandwidth	Number of Users	Maximum Mobile Speed
802.15 (PAN)	up to 55 Mbps	~few meters	~20 MHz	Dozens	Walking
802.11a,b,g (LAN)	up to 54 Mbps	~100 meters	a) g): 20 MHz b): 25 MHz	Dozens	Walking
802.16a,e	up to 30 Mbps	~ 10 km > with mult cells	1.75 to 20 MHz	Thousands	60 to 120 km/hr
802.20	~ 2 Mbps	~ 15 km > with mult cells	1.25 x N MHz N=1, 4, 8, 16	Thousands	250 km/hr
HiperPAN	Comparable to 802.15				
HiperLAN	Comparable to 802.11				
HiperMAN	Comparable to 802.16				

3.3.2 Selection of Evaluation Candidates via Minimum Threshold Test

As stated previously, many of the wireless network standards have practical limitations that are not applicable to aeronautical communications. Because of this, it is not necessary to bring forward every single wireless network standard. We have reduced the number of wireless network candidates by applying the Minimum Threshold Test process (described in section 2.3.3) to the 802.xx technology family. Table 3.3-2 lists all of the wireless network standards and gives rationale for filtering out some and bringing forward others. The candidate solutions we have selected to evaluate are identified in green. We should further note that while both 802.11 and 802.16 are chosen for evaluation, they comprise only a single candidate because they are considered to supplement each other. For example, 802.11 may be used for at-the-gate communications, but when a plane leaves the gate a handover is made to an 802.16 network that covers the airport surface.

Table 3.3-2: Application of Minimum Threshold Test to 802.xx Family of Standards

System	Evaluate	Rationale
IEEE 802.11a) g)	Yes	This is a proposal to the ICAO ACP and is already being implemented to provide AOC communications <i>at the gate</i> and in localized surface areas. Because of the limited range of the 802.11 standard, however, it is considered as a supplement to 802.16(e), and not as a stand-alone candidate
IEEE 802.15	No	Short range limits the applicability to <i>at the gate</i> communications, and does not offer any needed value beyond that offered by 802.11(a).
IEEE 802.16	Yes	This is a proposal to the ICAO ACP and it provides significant performance benefits over 802.11(a), particularly in the areas of QoS, achievable range, and mobility support. 802.16e is a particularly important element of the standard because it supports mobility
IEEE 802.20	No	This standard is not mature. While it aims to provide better mobility support than 802.16(e), if successful, it is likely that 802.20 capabilities will be absorbed by 802.16(e).
ETSI HiperPAN	No	Short range limits the applicability to <i>at the gate</i> communications, and does not offer any needed value beyond that offered by 802.11.
ETSI HiperLAN	No	Comparable technology and performance with 802.11, but with limited market success to date; provides little benefit beyond 802.11 although its MAC is considered superior to the 802.11 CSMA/CA MAC in providing QoS; however, 802.11 evolution is incorporating some of the attractive features of HiperLAN and 802.16e provides a more capable MAC than HiperLAN; thus consideration of HiperLAN adds no additional value over that provided by 802.11 and 802.16e.
ETSI HiperMAN	No	Comparable technology to (and performance of) 802.16. HIPERMAN has adopted 802.16 as its initial baseline, thus HIPERMAN provides no value beyond that offered by 802.16e.

3.3.3 Technology Description

The two candidate solutions brought forward from the previous section are described in this section in accord with the Services Provided and Key Features, Functional Architecture, and Air Interface.

3.3.3.1 Services Provided and Key Features

The 802.xx family of services is composed protocols limited to Layer 1 and Layer 2 that provide Bearer communications services. The following Bearer services for data transport mechanisms are offered by both 802.11 and 802.16 technologies.

- Unicast data
 - Unacknowledged connectionless
 - Acknowledged connectionless
 - Connection Oriented
- Broadcast/Multicast

Additionally, 802.16 offers some important QoS features for its Bearer services:

- **Unsolicited Grant Service (UGS)**—Defined to support services that generate fixed-length packets on a periodic basis. Service pre-allocates periodic grants to the SSs. This grant size is a system parameter and is negotiated at connection setup and is a part of the service agreements.
- **Real-Time Polling Service (rtPS)**—Targets applications that need real-time service flows, but generate variable sized data packets, such as VoIP, streaming audio, and streaming video. This service scheme ensures periodic request opportunities, which can be used by the SS to request for a specific grant in real-time.
- **Non-Real-Time Polling Service (nrtPS)**—Designed for non-real-time applications such as bulk file transfers that may need high bandwidth allocations, but can tolerate longer delays.
- **Best Effort Service (BE)**—Provides services to best effort traffic where throughput or delay guarantees are not provided.

Teleservices are provided in an 802.xx network by applications at the network layer or above, but 802.11 and 802.16 do provide support lower layers. The 802.16 MAC layer can provide rtPS for responsiveness VoIP and efficient use of spectrum. The MAC layer can also provide UGS to provide dedicated bandwidth for a voice channel. Figure 3.3-4 shows the protocol stack of VoIP over 802.16.

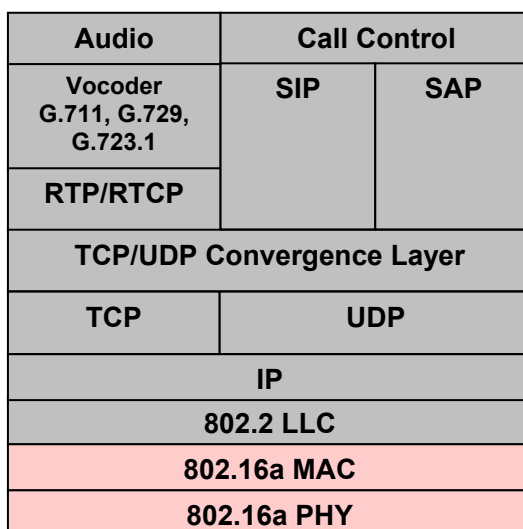


Figure 3.3-4: Protocol Stack of VoIP over 802.16

Supplementary services offered by 802.xx technologies are security (authentication, authorization, privacy, etc.) and mobility management (e.g., handoffs, etc.).

3.3.3.2 Functional Architecture

The family of 802.xx wireless networks has two basic topologies: Basic Service Set (BSS) and Independent BSS (IBSS). A BSS is a set of stations controlled by a single Access Point (AP). BSS supports point-to-point (PTP) communications between the AP and a subscriber and also supports point-to-multipoint (PTM) communications between the AP and its subscribers. Both 802.11 and 802.16 support BSS. Figure 3.3-5 shows the BSS topology, also referred to as “Infrastructure” mode.

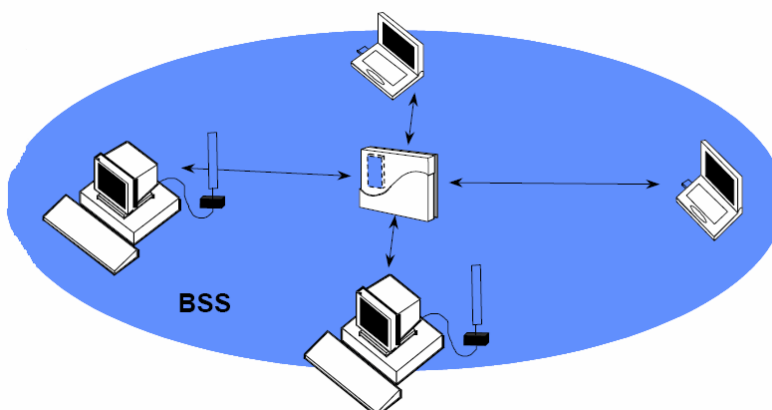


Figure 3.3-5: Basic Service Set (BSS)

An IBSS is a self-contained network without a dedicated access point. IBSS provides a ‘Mesh’ network with peer-to-peer (P2P) communications. Figure 3.3-6 shows the IBSS topology, also referred to as “Ad Hoc” mode.

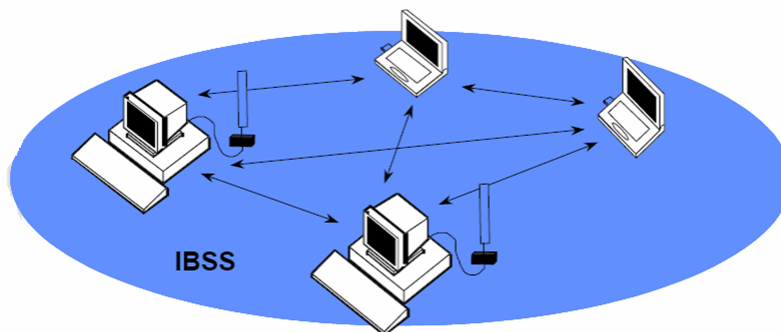


Figure 3.3-6: Independent Basic Service Set (IBSS)

Figure 3.3-7 illustrates that all of the 802.xx protocols are at layer 1 and 2, with the exception of security supplemental services. Accordingly, in a complete architecture that provided a suite of teleservices, elements are required outside of the 802.xx standard that support such services. This is illustrated in Figure 3.3-8, which shows a set of components completing an 802.16 architecture.

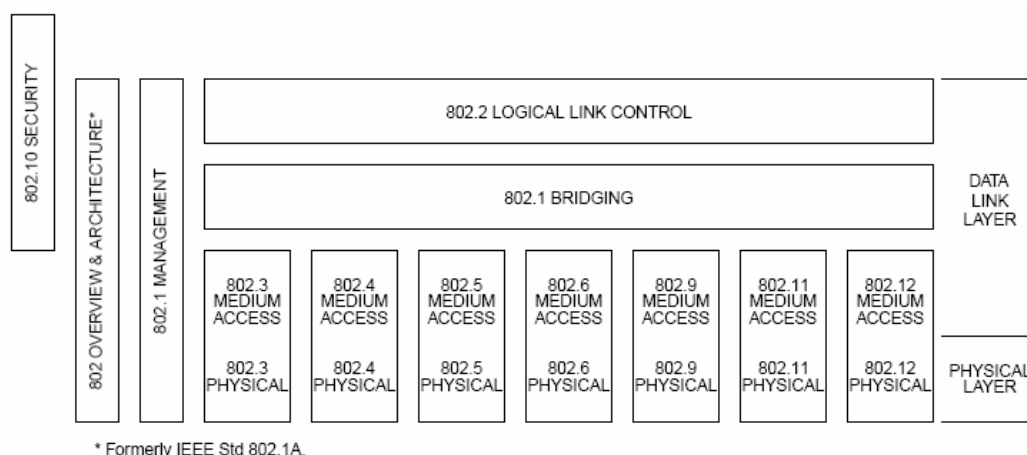


Figure 3.3-7: IEEE 802.11 and 802.16 Protocols in Context

All of these components are IP compliant since 802.16 is designed to work with the IP suite above it. The illustrated Router/Gateway would provide access to the Internet and to the PSTN as well, if configured to support VoIP. The Dynamic Host Control Protocol (DHCP) server provides a network address to any mobile user that enters the net. MAC layer security is provided, but an Authentication Service would also provide security at the application layer.

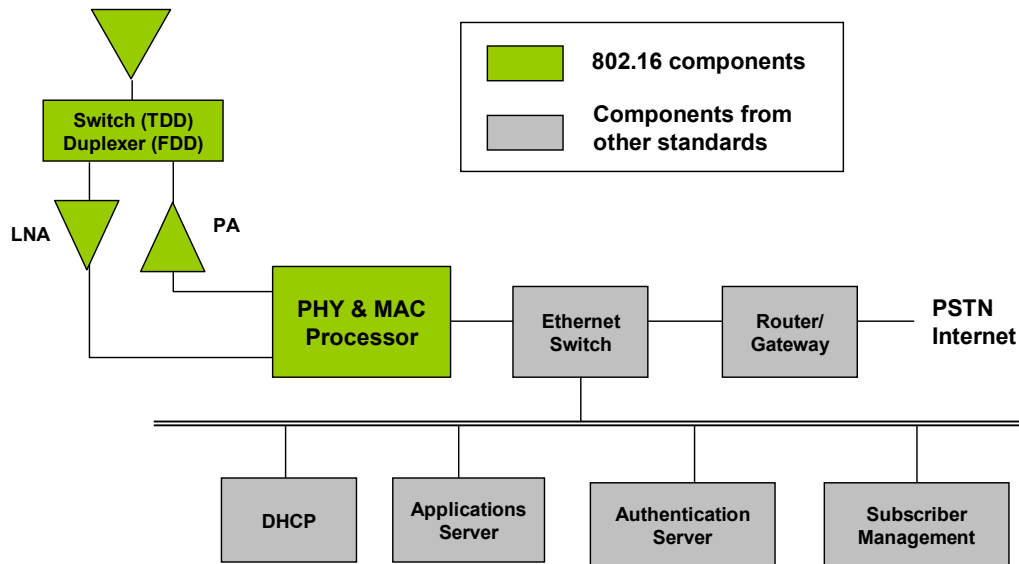


Figure 3.3-8: Example 802.16 Architecture

3.3.3.3 Air Interface Description: PHY, MAC, and Network

802.11(b) is a Direct Sequence Spread Spectrum (DSSS) waveform similar to the CDMA waveforms of cellular telephony. 802.11(a), and (g) use Orthogonal Frequency Division Multiplexing (OFDM), similar to the modulation used for wireline DSL. OFDM is also used in digital TV and radio broadcasting, public safety radio, 3G/4G cellular, and many others. 802.11 uses a 20 MHz bandwidth divided into 64 sub-carriers with 312.5 kHz spacing. 48 of these sub-carriers are used for data modulation. 4 sub-carriers are used for pilot signals to provide phase reference for the channel across the frequency band. 11 sub-carriers are unused to provide the frequency guard band. The DC sub-carrier is not used. The modulation and coding of the sub-carriers is tailored to the desired data rate. BPSK, QPSK, 16QAM, and 64QAM are all supported to provide data rates up to 54 Mbps. The formula for the supported coded bit rate is as follows:

$$\begin{aligned} \text{Coded Bit Rate} &= N_M \times R \times 48 \times 250 \text{ kbps} \\ \text{where, } N_M &= 1 \text{ for BPSK, } 2 \text{ for QPSK, } 4 \text{ for 16QAM, } 6 \text{ for 64QAM} \\ \text{and } R &= \frac{1}{2}, \frac{2}{3}, \frac{3}{4} \text{ coding rates} \end{aligned}$$

IEEE 802.16 uses 256 sub-carrier OFDM and also includes an option for 2048 sub-carrier OFDM. In the former, 192 sub-carriers are used for data modulation. 8 sub-carriers are used for pilot signals to provide a phase reference across the frequency band. 55 sub-carriers are used for guard band. The DC sub-carrier is not used. 802.16 uses variable bandwidths ranging from 1.75 to 20 MHz in increments. 802.16 supports QPSK, 16QAM and 64QAM. The formula for the supported coded bit rate is as follows:

$$\begin{aligned} \text{Coded Bit Rate} &= N_M \times R \times 192 \times \text{BW}/256 \\ \text{where, } N_M &= 2 \text{ for QPSK, } 4 \text{ for 16QAM, } 6 \text{ for 64QAM} \\ \text{and } R &= \frac{1}{2}, \frac{2}{3}, \frac{3}{4} \text{ coding rates} \\ \text{and } \text{BW}/256 &\text{ is the variable sub-carrier spacing} \end{aligned}$$

Figure 3.3-9 shows how the 256 sub-carriers of 802.16 are spaced out in the channel.

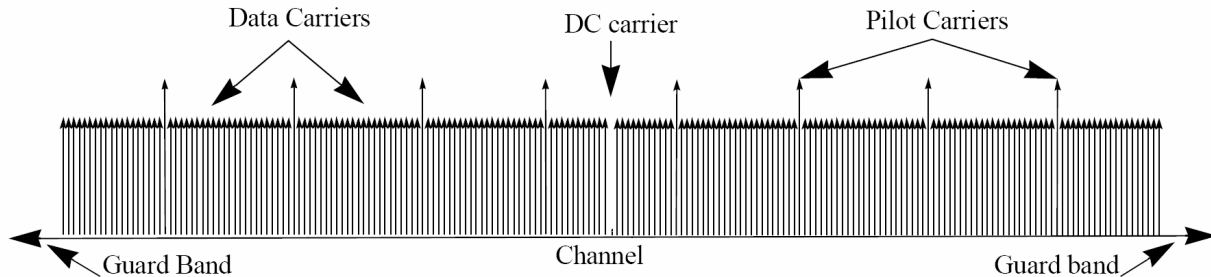


Figure 3.3-9: Sub-carrier Spacing for 802.16

3.3.4 Concept of Use: Application to Aeronautical A/G Communications

In this concept of use section, the application of wireless networks standards to aeronautical communications is described, and this provides the basis for subsequent evaluation. This concept of use description involves the following elements:

- Applicable Airspace: the airspaces in which cellular technology can practically provide aeronautical communications
- Applicable Frequency Band: the band or bands that are appropriate for the implementation of cellular technology for aeronautical communications
- Services Used: the cellular services that are best applicable to aeronautical communications
- Architecture Integration: description of how the cellular architecture integrates into the architecture for aeronautical communications.

Each of these is, in turn discussed below.

3.3.4.1 Applicable Frequency Band

The 802.xx family is best deployed in the MLS band (5091 to 5150 MHz) because of its ample and appropriate spectrum to accommodate wideband waveforms. The MLS band is also within the design range for both the 802.16 and 802.11 standards. Figure 3.3-10 illustrates a notional definition of FDD channels for 802.xx technology.



Figure 3.3-10: Notional Definition of 802.16 FDD Channels

3.3.4.2 Applicable Airspace Environment

Because of the relatively short design RF range of 802.16(e) and its support for only low speed mobile platforms, its applicability is limited to communications on the Airport Surface. However, within that constraint, 802.16 seems an ideal candidate to provide robust and high data rate communications with aircraft and other vehicles on the airport surface. 802.16(e) can provide surface coverage over an entire airport, using multiple cells as needed to provide complete coverage. 802.11 can provide coverage at hotspots such as busy gates. 802.xx mobility management features will support provide handovers from 802.11 LANs to 802.16 WANs.

3.3.4.3 Applicable Wireless Network Services

Figure 3.3-10 illustrates a notional mapping between alternative data transport bearer services offered by 802.16 and the voice and data needs of aeronautical communications. Note that critical voice and data needs may be met via bearer service that pro-actively reserve data (UGS) or rapidly (rtPS) in response to spontaneous events.

Table 3.3-3: Applicability of 802.16 Services to Meet Communications Needs

Alternative Data Transport Services	Group Voice Conference	A/G and G/A Addressed Voice	A/A Voice (direct)	Broadcast Voice	A/G and G/A Addressed Data	G/A Broadcast Data	A/A Data (direct)
Unsolicited Grant Service (UGS)	✓	✓	✓	✓	Dependent Surveillance	✓	✓
Real-Time Polling Service (rtPS)	✓	✓	✓	✓	Emergency Tactical	✓	✓
Non-Real-Time Polling Service (nrtPS)	No	No	No	No	Strategic Information	✓	✓
Best Effort Service (BE)	No	No	No	No	No	No	No

3.3.4.4 Architecture Integration—Service Provider Infrastructure

Figure 3.3-11 illustrates a notional mapping of 802.xx elements into the NAS infrastructure.

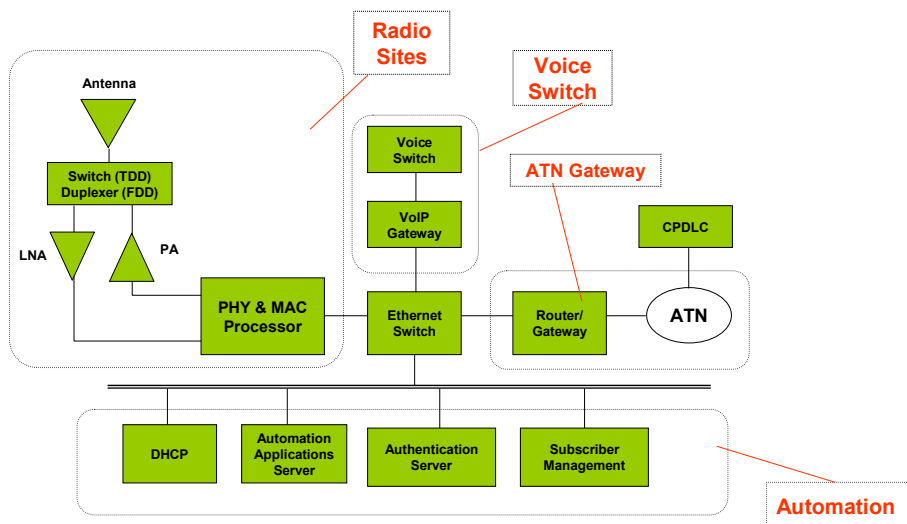


Figure 3.3-11: Notional Integration of 802.16 with the NAS

3.3.4.5 Architecture Integration—Avionics

Figure 3.3-12 illustrates a notional integration of 802.16 elements with aircraft avionics. The elements in green indicate the equipment that would be required for A/G communications via wireless network technology.

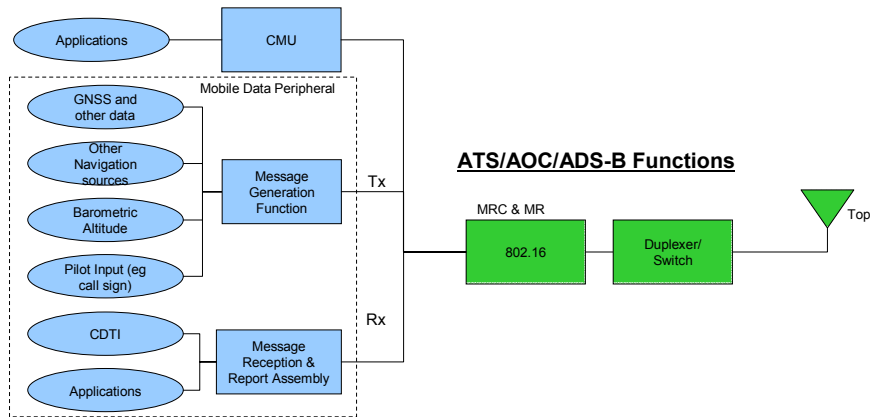


Figure 3.3-12: Notional Integration of 802.16 with Aircraft Avionics

3.3.5 Evaluation Summary and Scores

Table 3.3-4 provides the scoring summary for 802.16. The rationale for the assigned scores is provided in table 3.3-5.

Table 3.3-4: 802.16 Evaluation Worksheet

	Criteria	Surface	Terminal	En Route	Oceanic	Polar
Voice Needs	1					
Pilot-Controller Talk Group	1A1					
Pilot-Controller Selective Addressing	1A2					
Direct Pilot-Pilot	1A3					
Broadcast capability	1A4					
Capacity provided	1B1					
Address space	1B3					
Aircraft mobility management	1C1					
Latency	1C2					
Basic Data Needs	2					
A/G and G/A Addressed Data Transport	2A1					
Ground-to-Air Broadcast Data Transport	2A2					
Aggregate Data Rate	2B1					
Number of Users	2B2					
Uplink and Downlink Priority Levels / QoS	2C1					
Latency	2C2					
Enhanced Data	3					
ADS-B	3A1					
Pilot-Pilot Data Transport	3A2					
Aggregate Data Rate	3B1					
Technology Readiness Level	4					
Standardization Status	5					
Certifiability	6					
Ground Infrastructure Cost	7					
Cost to Aircraft	8					
Spectrum Protection	10					
Security	11					
Transition	12					

Table 3.3-5: 802.16 Scoring Rationale

Element	Score	Rationale
Pilot-Controller Talk Group	Green (S) Red (T, E, O, P)	Standard supports streaming media; group conference calls supported via SIP/VoIP.
Pilot-Controller Selective Addressing	Green (S) Red (T, E, O, P)	Standard supports streaming media; selective address calls supported via SIP/VoIP.
Direct Pilot-Pilot	Green (S) Red (T, E, O, P)	Standard supports direct A/A communications via mesh communications.
Broadcast capability	Green (S) Red (T, E, O, P)	Broadcast via layer 2 broadcast address and IP multicast.
Capacity provided	Green (all domains)	10 MHz of spectrum could support large number of talk groups and other voice channels.
Address space	Green (all domains)	Supports thousands of users.
Aircraft mobility management	Green (S) Red (T, E, O, P)	Supports mobility between multiple cells on an airport surface.
Latency	Yellow (all domains)	Standard supports QoS so that calls should be set up in timely fashion with low latency, but perhaps not at the level required for voice.
A/G and G/A Addressed Data Transport	Green (S) Red (T, E, O, P)	Addressed via mobile IP.
Ground-to-Air Broadcast Data Transport	Green (S) Red (T, E, O, P)	Broadcast via layer 2; broadcast address and IP multicast.
Aggregate Data Rate	Green (all domains)	Standard supports many Mbps in available bandwidth.
Number of Users	Green (all domains)	Supports thousands of users.
Uplink and Downlink Priority Levels/QoS	Green (all domains)	Standard supports QoS
Latency	Green (all domains)	Standard supports QoS and has sufficient bandwidth to deliver high priority data quickly.
ADS-B	Green (S) Red (T, E, O, P)	Standard supports direct A/A communications
Pilot-Pilot Data Transport	Green (S) Red (T, E, O, P)	Standard supports direct A/A communications.
Aggregate Data Rate	Green (all domains)	Standard supports multiple Mbps data rate.
Technology Readiness Level	Green	802.16 function and performance requirements have been designed and demonstrated in an environment comparable to airport surface.
Standardization Status	Yellow	802.16 is an adopted IEEE standard with extensive vendor support.
Certifiability	Red	802.16 is not designed and developed to a safety related standard.
Ground Infrastructure Cost	Green	Expect that COTS equipment may be used for the ground infrastructure.
Cost to Aircraft	Green	Cost estimate is comparable to VDL 3.
Spectrum Protection	Yellow	802.16 fits into both the MLS or DME spectral bands.
Security	Green	802.16 provides authentication and integrity.
Transition	Green	Supports incremental deployment and operational transparency.

In summary, private service providers have already shown interest in the 802.xx family of wireless protocols: SITA is offering ‘gatelink’ service based on 802.11 that provides data link to aircraft at the gate and has shown interest in 802.16e at public presentation. IEEE 802.16 provides the opportunity to utilize the MLS spectrum to support a broad scope of communications needs, both data and voice, over the entire airport surface. Increased data rates on the airport surface that might not be met by a future system in the DME band, could be met by a fully COTS system base on 802.16e in the MLS band. The business case for 802.16 infrastructure may be driven by factors beyond ATS and AOC communications. For example, airport authorities may desire to support airport fixed services to support airport infrastructure. At current time, 802.16e mobility addresses mobile speed less than 120 km/hr and so will not support aircraft on landing and takeoff. This is an issue to address in future consideration of 802.16e for aeronautical applications.

3.4 Public Safety Radio

This section provides details and background on Public Safety Radio standards and systems in use for public safety and service communications. Public Safety Radio systems are a subset of Land Mobile Radio Systems (alternatively known as Private Mobile Radio and Public Access Mobile Radio). These systems are used to provide communications for safety of life services, including police department, fire, search and rescue, and also fulfill other government communications requirements.

As a prelude to the technology evaluation, a representative sampling of Public Safety Radio standards and systems was assembled. An attempt was made to determine the technologies in use today, and to determine the technical parameters of systems that met one of two criteria for consideration as technologies applicable to future aeronautical communications:

1. Systems that either have publicly available standards, or
2. Systems that are proprietary but provide useful features (such as spectral efficiency) or potentially novel technology.

This section presents the results of this investigation and provides an overview of the technologies that were determined to meet these criteria. A brief history is provided of the dominant standards (APCO and TETRA). Because it proves useful for comparison purposes, a schema for system categorization is developed. The Public Safety Radio technologies are then categorized, and where appropriate a representative technology was selected for further evaluation.

Not all of the categories of Public Safety Radio technologies that were investigated appeared to provide real value as technologies applicable to future aeronautical communications. Some of the Public Safety Radio technologies were eliminated from detailed evaluation because they were considered to be inapplicable. Those that were selected for evaluation are described in detail in this section to provide the technical basis for the technology evaluations. Technology descriptions include the communications services provided by the technology as well as the key features of the technology.

To assess the application of this technology to aeronautical A/G communications, a system functional architecture is provided, and the air interface described. This leads to a description of the concept of use of this technology for aeronautical A/G communications, including a notional physical architecture, applicable services, and a frequency assignment plan.

Finally, the technologies are evaluated and scored. From the scoring, some observations are offered that complement the evaluations and provide insight as to the applicability of a technology to the functional, performance and institutional requirements of future aeronautical communications.

3.4.1 *Overview of the Family*

The survey of Public Safety Radio systems produced a large set of potential candidates for future aeronautical communications. These systems can be loosely grouped into standardized systems with open interfaces, and proprietary systems that either provide useful features or potentially novel technology. The standardized systems with open interfaces include:

- APCO Standards—Developed by TR-8 Private Radio Technical Standards Committee, under sponsorship of the TIA in accord with a memorandum of understanding between TIA and APCO/NASTD/FED (Association of Public Safety Communications Officials/National Association of State Telecommunications Directors/Federal Government), the APCO standards

include Project 25 (P25) and Project 34 (P34). Project 25 is a narrowband (12.5 kHz) digital voice and data system that can operate in either a trunked⁶ mode or a conventional radio mode, and provides direct mobile-radio to mobile-radio communications as well as a full duplex base-station repeater mode. Project 34 is a wideband system (50, 100, and 150 kHz channels are defined) that provides high data rate IP based services to public safety mobile users.

- TETRA Standards—Produced by the Project Terrestrial Trunked Radio (TETRA) Technical Body of the European Telecommunications Standards Institute (ETSI), the TETRA standards have two releases, TETRA Release 1 and TETRA Release 2. The TETRA Release 1 system is a narrowband system (25 kHz) using 4-slot TDMA to provide digital voice and data to up to four simultaneous users. TETRA Release 2 systems will be capable of providing much higher data rates, and like the APCO P34 systems, have been specified to use 50, 100, and 150 kHz channels.
- TETRAPOL—Development of the publicly available specifications for TETRAPOL has been carried out by the manufacturers of the TETRAPOL Forum and the TETRAPOL Users' Club. The TETRAPOL system provides digital voice and data using Frequency Division Multiplexed narrowband channels (both 10 and 12.5 kHz channels are defined).
- IDRA—Standardized by the Association of Radio Industries and Businesses (ARIB). The first version of Japan's digital dispatch standard, called RCR STD-32, was completed in March 1993. An updated version of this standard, which did not alter the basic RF characteristics of the standard, but did add substantial networking capability to the system, was approved in November 1995, and is referred to as RCR STD-32A. The IDRA system uses quad-carrier 16-level QAM to provide a data rate of 64 kbps in a 25 kHz channel. The system uses six-slot TDMA to provide simultaneous access to up to six users on the same RF channel.

The proprietary systems included:

- Integrated Digital Enhanced Network (iDEN™) (referred to internationally as DIMRS)—Proprietary Motorola narrow-band TDMA voice and data system that is functionally equivalent to IDRA. The iDEN™ system uses quad-carrier 16-level QAM to provide a data rate of 64 kbps in a 25 kHz channel. The system uses six-slot TDMA to provide simultaneous access to up to six users on the same RF channel.⁷
- EDACS (Enhanced Digital Access Communications System)—EDACS was created by General Electric and then further engineered by Ericsson. The EDACS technology has changed numerous owners and now is currently owned by M/A Com. Standardization of the air interface through EIA has been conducted, and is available as EIA TSB 69 series of standards. The RF interface uses either 25 or 12.5 kHz channels. The data rate provided is low, primarily because of the GFSK modulation employed (and the small channel bandwidth). 9.6 kbps is supported on 25 kHz channels, and 4.8 kbps on 12.5 kHz channels.

Of the systems listed above, the APCO (P25 and P34) and ETSI (TETRA) standardized systems are the most important, first because they are the public domain (open) standards for the geographical region that is the focus of this study, and secondly, because they are evolving towards more capable systems providing high data rates. This evolution has provided wideband Public Safety Radio systems that seem to be viable candidates for future aeronautical communications. An abbreviated history of these standards is provided in the following paragraphs.

3.4.1.1 Project 25

As a consequence of FCC allocation of new spectrum (roughly 30 MHz in the 806 to 866 MHz band) in 1976, a study was commissioned by APCO to provide technical guidance for its utilization. This study was termed Project 16, and provided reports and recommendations on use of the allocated radio spectrum for public safety communications.^{8, 9, 10} The first radio systems built and deployed in accord with the

Project 16 recommendations were analog trunked radio systems. All of these systems were proprietary, as it was not until very recently that open standards for Public Safety Radio have been developed.

The first such specification, APCO Project 25, commenced in 1989, with the goals of ensuring backwards compatibility with analog systems, achieving improved spectrum efficiency, and providing a migration path between analog and digital systems. Standardization was moved to the control of the Telecommunications Industry Association (TIA) in 1990, and has been under the TIA Committee on Mobile and Personal Private Radio Standards (TR-8) ever since. The first P25 standards were TIA Bulletins, and came out between 1994 and 1996. Additional P25 documentation, in the form of TIA Interim Standards, followed in early 1996, with the vocoder being standardized in May 1998.

P25 standardization is ongoing, with a Phase II standard based on two-slot TDMA on 12.5 kHz FDM channels under development. The expected release of the Phase II standards is in the 2005 to 2006 time frame. The primary difference between Phase I and II is the improved spectrum utilization of one voice channel per 6.25 kHz of channel bandwidth provided in Phase II. Additional standards goals include interoperability with legacy equipment, increased roaming capacity and improved spectral efficiency/channel reuse. Other Phase II standardization efforts include console interfacing, interfacing between repeaters and other subsystems (e.g., trunking system controller), and man-machine interfaces for console operators that would facilitate centralized training, equipment transitions and personnel movement.¹¹

3.4.1.2 Project 34

Project 34 was started to complement Project 25 data capabilities with a broadband data system in the 700 MHz band. The following, extracted from TIA documentation, describes the P34 standardization activities [bolding added for emphasis]:

*Recognizing the need for high-speed data for public safety use, as expressed in the Public Safety Wireless Advisory Committee (PSWAC) final report, among others, the P25 standard committee established the P25/34 Committee to address Phase III implementation. Similarly to the P25 approach, the standard committee established the P25/34 user forum to address this issue. Phase III activities are addressing the operation and functionality of a new **aeronautical** and terrestrial wireless digital wideband/broadband public safety radio standard that could be used to transmit and receive voice, video, and high-speed data in a ubiquitous, wide-area, multiple-agency network. On June 1, 1999, the P25/34 committee released the Statement of Requirements for a wideband **aeronautical** and terrestrial mobile digital radio technology standard for the wireless transport of rate intensive information.*¹²

The P34 system is fully standardized at this time, with most of the standards published and available for purchase through EIA/TIA. To demonstrate the system capabilities, an operational system has been deployed in Pinellas County, Florida, providing wideband data at 700 MHz.

3.4.1.3 TETRA

Terrestrial trunked radio (TETRA) was developed by the European Telecommunications Standards Institute (ETSI), which established a memorandum of understanding (MoU) in 1994 as a joint effort of users, manufacturers, operators and regulators to support ETSI in the standardization process. Work on the TETRA standard was started in late 1989. The TETRA standard was produced within ETSI by voluntary work by both users and manufacturers, and was funded by ETSI and the European Union commission. The core TETRA standards were voted full European Telecommunication Standard status in December 1995; and the first TETRA systems became operational during 1997.

A nominal three year work program was started in 2001 to develop the TETRA II standards. The program goals were to standardize the TETRA Advanced Packet Service (TAPS) and the TETRA Enhanced Data Service (TEDS), as well as to select and standardize other speech codecs and evolve the TETRA Subscriber Identity Module (SIM). TAPS, the TETRA Advanced Packet Service, was intended to be a TETRA I overlay network. It is based on E-GPRS technology. The TAPS standards are complete at this time. TEDS, the TETRA Enhanced Data Service, is being designed to provide full Compatibility with TETRA 1, and standardization is currently in progress.

3.4.1.4 Project MESA

Finally, a word of description of the cooperative effort to develop the Project MESA system is in order. ETSI and TIA have agreed to work collaboratively for the production of mobile broadband specifications for public safety. During an April 2000 meeting, a draft agreement between ETSI and TIA, proposing the creation of a Public Safety Partnership Project (PSPP), was approved. On May 25, 2000, ETSI Director General Mr. Karl-Heinz Rosenbrock and TIA Vice President Mr. Dan Bart formally signed the PSPP agreement. The current Partnership Agreement for Project MESA was modified and ratified January 2001 in the City of Mesa, Arizona. The Project was given the name MESA (Mobility for Emergency and Safety Applications) at that time.

3.4.1.5 Evolution of the Standards

Figure 3.4-1 shows the evolution of US and European public safety radio standards.

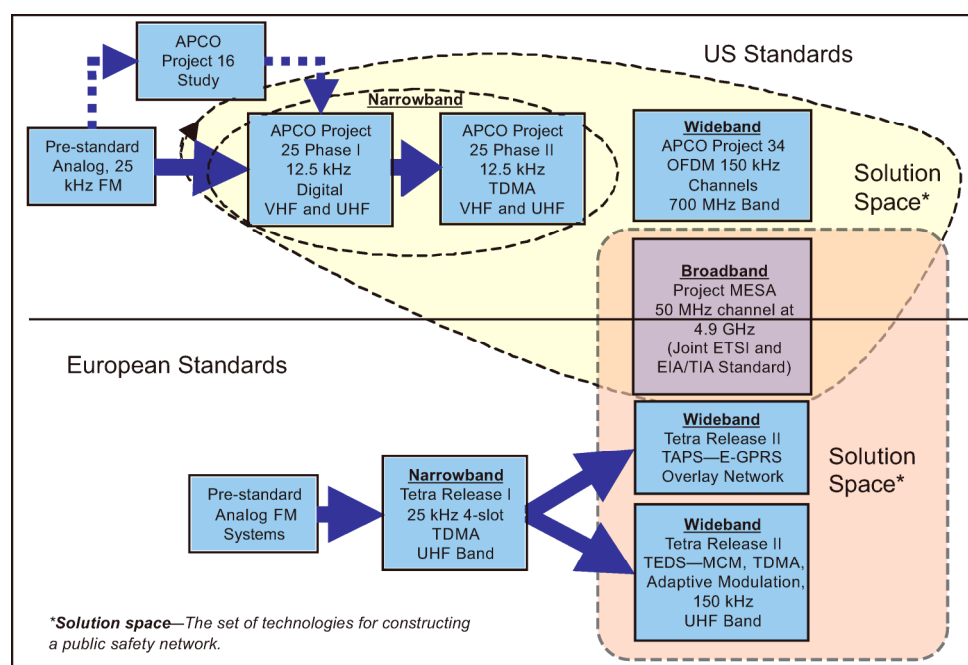


Figure 3.4-1: US and European Standards, Their Evolution, and Characterization

It is important to note in figure 3.4-1 that the APCO standards are complementary. APCO P25 systems (either Phase I or Phase II) are intended to provide digital voice and data services with near continuous coverage in the Continental US, while P34 systems are deployed in tandem, providing high data rate data services. MESA systems are likely to be incident specific (e.g., nodes on fire trucks and police cars) rather than based on a fixed infrastructure. Hence, the *solution space* for a public safety network may very likely include P25, P-35, and Mesa systems.

In Europe, the TETRA standards are being evolved with the TEDS specification, and most of the higher layers of the TETRA protocol are being reused. TEDS is being specified to provide the 25 kHz channelization of TETRA Release I, as well as the Wideband channelizations of P34 (50, 100, and 150 kHz), so it becomes the *de facto* European standard for both Narrowband Voice and data (the TETRA Release I improvement) and Wideband data, with Mesa systems providing broadband data as required. Most of the European literature is quick to point out that TEDS is not a replacement of TETRA Release I, but rather an improvement, as in the following quote:

"A number of air interface enhancements have been identified and included in the work plan. These enhancements are not replacing TETRA release 1 but improving its performance! More than 99.9 % of TETRA release 1 is still valid, applicable and available today!"¹³

3.4.1.6 Public Safety Radio Classification Schema

After studying the identified technologies, a schema that differentiated between system bandwidth and user access scheme was developed. In terms of bandwidth, the Public Safety Systems being considered lend themselves to classification as Narrowband, Wideband or Broadband systems. The multiple access classifier further distinguishes between FDM and TDM systems.

The bandwidth classifiers, and a brief description of system characteristics and purposes, are:

Narrowband systems are characterized by small channel bandwidths. Channel bandwidths are typically either 12.5 or 25 kHz. These systems are primarily used for voice communications, although they do provide data services. Data rates provided are low, and are measured in the tens of kilobits per second.

Wideband systems are being developed to provide higher data rate services. These systems are specified to have channel bandwidths of 50, 100, or 150 kHz, and provide data rates that are measured in the hundreds of kilobits per second. The 2003 World Radiocommunications Conference (WRC 2003) designated harmonized frequency bands for wideband application for Public Protection and Disaster Relief (PPDR). In the view of the International Telecommunications Union (ITU), the purpose of wideband systems is to provide digital voice and medium speed data on wide area networks. Applications include near real-time video, sensory data, vehicle status, fingerprint (biometrics), identifying persons, maps, and medical records.

Broadband systems having the potential to provide megabits per second of data. The current allocation is 50 MHz of spectrum at 4.9 GHz. Worldwide allocations of broadband systems will be discussed at the next WRC. The view of the ITU for broadband systems is for local/tailored area networks and hot spots providing very high speed data. Applications include high quality digital real time video (e.g., video clip-on cameras used by in-building fire rescue or remote medical support personnel) and surveillance of crime scenes including use of remote control robotic devices.

The multiple access classifier definitions are:

TDM systems use a communications technique that uses a common channel for communications among multiple users by allocating unique time slots to different users. In order to keep the slots orthogonal, guard bands must be defined. These guard bands determine the maximum extent of a cell, as a user that is too far removed will have his (delayed by propagation) slots interfere with other users transmissions.

FDM systems create simultaneous, continuous channels from a transmission medium by assigning a separate portion of the available frequency spectrum to each of the individual channels. User group transmissions are on a particular frequency, and frequency reuse rules are developed to control

interference between user groups. The current VHF analog AM system is an FDM system. Communications ranges are typically limited by transmitter power, receiver sensitivity and effective antenna heights in FDM systems.

Table 3.4-1 shows the Public Safety Radio technologies that were considered, as partitioned by this classification scheme. Two of the cells are blank, and would have provided attractive candidates if representative systems could have been found. In general, most commercial TDMA systems do not provide sufficient guardband for use in aeronautical communications, and the Public Safety Radio technologies are no exception. These technologies are typically designed for cell radii of 40 miles or less; primarily due to the range restriction imposed by small handheld radios (typical subscriber units are either vehicular mounted or handheld), which include low power, small antenna aperture, and low antenna effective height. Range restrictions of the FDM systems tend to be more amenable to modifications than the range restrictions of TDM systems, as changing the TDM slot structure can require extensive protocol modifications. Consequently, when selecting technologies to evaluate, preference was shown for FDM systems.

The question mark associated with the classification of MESA is related to the fact that this project is currently in the requirements phase. Hence, there are no system specifications for MESA, and it is impossible to know precisely what multiple access schemes will be employed. However, the notional bandwidth of 50 MHz makes it unlikely that an FDM scheme will be used. Classification of the system as a TDMA system represents an educated guess.

Table 3.4-1: Public Safety Radio Technologies Considered, by Category

	Narrowband	Wideband	Broadband
TDMA	APCO P25 Phase 2 TETRA Release 1 IDRA iDEN	APCO P34 Tetra Release 2—TAPS Tetra Release 2—TEDS	MESA?
FDMA	APCO P25 Phase 1 TETRAPOL EDACS		

3.4.2 Selection of Evaluation Candidates

The classification scheme shown in table 3.4-1 provides three major groupings of technologies, Narrowband, Wideband and Broadband. Within each of these groupings, a secondary distinction was made between TDMA and FDMA. In essence, these bins were chosen such that all of the technologies in a particular bin are essentially homogeneous. Within the fidelity of a pre-screening analysis, selection of any one of these technologies for evaluation is likely sufficient to provide insight into the whole class of technologies.

As an example, consider the Narrowband FDMA bin. The member technologies are APCO P25 Phase 1, TETRAPOL and EDACS. All of these technologies will provide services that are well matched to the needs of aviation by virtue of their membership of the class of Public Safety Radio systems.¹⁴ They all will provide the right kind of voice services, and about the same amount of data capabilities, by virtue of their common channel bandwidth. In this case, evaluation of one technology is sufficient, with the caveat that should that technology be recommended for further study, all of the members of that classification bin should also be brought forward for further study. This is the recommended strategy for trade study down-selection published in the FAA System Engineering Manual [bolding added for emphasis]:

*When numerous possible alternatives are identified, a detailed analysis of each one may not be cost-effective; therefore, down-selection of candidates is recommended. Identifying high-risk candidates and candidates with questionable feasibility or high lifecycle cost helps to reduce the number of alternatives to be studied. Screening the alternatives against the selection criteria eliminates these candidates. **If one of a closely grouped set of alternatives is down-selected, it is recommended that all alternatives in that group be down-selected.** Any relationship that is not the same for each down-selected alternative and the baseline becomes part of the detailed Trade Studies.¹⁵*

However, not all of the bins have candidates that are closely grouped. The Wideband TDMA bin provides such an example. Here, the P34 TDMA guard bands are much larger than the Tetra Release 2—TAPS and Tetra Release 2—TEDS guard bands. One of the driving requirements for A/G communications is the required coverage of large sectors. A typical range requirement of 200 nmi is usually given. Many TDMA and Time Division Duplex systems simply do not provide an adequate guard band to communicate at this separation distance without burst overlaps. While coverage could be provided using selective-keying (referred to as a diversity site groups), the large cost of base stations makes this impractical unless the system range is relatively large. Table 3.4-2 provides the design ranges of the candidate technologies. The reader should be aware that this table is somewhat simplistic, especially for the P25 system, where the range limitation depends as much on system configuration and operating mode as it does on any design parameters of the air interface. (These details will be explained later in this section.)

Table 3.4-2: Design Range Limitations of Candidate Technologies

Classification	System	Range Limitation (km)
Narrowband TDMA	APCO P25 Phase 2	TBD*
	TETRA Release 1	3.8 to 17.5 ¹⁶
	IDRA	20 to 40 ¹⁷
	iDEN	5 to 40 ¹⁸
Narrowband FDMA	APCO P25 Phase 1	7.6 to 35 ¹⁹ (Trunked, Repeater-Configuration) Power limited** (Direct mode)
	TETRAPOL	8-28 ²⁰
	EDACS	Should be power limited**
Wideband	APCO P34	150 (IOTA) ²¹ 187.5 (SAM) ²²
	Tetra Release 2—TAPS	< 5 ²³
	Tetra Release 2—TEDS	< 5 ²⁴
Broadband	MESA	TBD*
Notes * Standards are not currently available for these systems ** While the FDM systems are in general power limited, this is not always the case. For certain system configurations, most notably the Trunked-mode and some Repeater-configurations, data reservation protocols require slotted Aloha reservation mechanisms, and the slot structure limits effective system range.		

With the previous discussion points in mind, representative technologies were selected from the Narrowband, Wideband and Broadband Public Safety Radio classifications for further analysis. The technologies selected, and the specific rationale for selection is described below.

3.4.2.1 Narrowband System Selected for Evaluation

This classifier has two sub-classes, TDMA systems and FDMA systems. From the previous discussion of design range of Public Safety Radio systems, the design ranges in able 3.4-2 should not be unexpected. The design range limitations of the TDMA systems are inherent, and it can require significant changes to

the air interface to extend these ranges. While some of the FDMA systems also have design range limitations, these are not applicable to all of the modes of operation, and in fact, some of the modes are only power limited. A decision to not select any of the TDMA Narrowband technologies for further analysis was made.²⁵

The Narrowband FDMA bin consisted of three systems, P25 Phase I, TETRAPOL and EDACS. These systems were considered functionally equivalent, with the absence of a design range for EDACS being more than offset by the proprietary nature of the technology and the low data rate that it offered (the ultimate conclusion of this study was that all of the narrowband technologies would be down-selected, and the primary driver for this conclusion was the low offered data rates of these technologies). It was decided to treat these technologies as a closely grouped set. Using the FAA System Engineering methodology quoted above, one of the group would be selected for evaluation. Should it be determined that this technology was recommended for further study, the entire closely grouped set would be recommended. P25 was selected for evaluation from this closely grouped set.

3.4.2.2 Wideband System Selected for Evaluation

The choices for evaluation were APCO P34, Tetra Release 2—TAPS, and Tetra Release 2—TEDS. From the design range limitations presented in table 3.4-2, it is clear that APCO P34 is the most closely suited for the application to aeronautical communications of the three candidates. P34 was selected for evaluation on this basis. Furthermore, it was not felt that TEDS and TAPS are really comparable to P34 due to the large disparity in system design range. Hence, it was not deemed appropriate to bring TEDS and TAPS forward if P34 was down selected (the FAA system engineering methodology quoted previously only applies if all of the candidates have roughly the same applicability). In this case, P34 is clearly the best of breed, providing the same capabilities as the other members of its family and being much more readily applied to the application of interest, air-ground communications for relatively large communications distances. P34 was selected for evaluation, and TEDS and TAPS were not further considered in this study.

3.4.2.3 Broadband System Selected for Evaluation

The only broadband Public Safety Radio technology that was identified is Project MESA. Project MESA is at the requirements definitions phase, and provides no real substance that can be evaluated as a consequence. Given the accelerated development schedule for the future aeronautical communications system, and the emphasis placed on technical maturity, it was determined that no candidate in this category would be evaluated.

Table 3.4-3 provides a synopsis of the above discussion. As shown in the Table, Project 25 and Project 34 were those technologies selected for further evaluation. This evaluation is provided in the following sections.

Table 3.4-3: Public Safety Radio Systems Selected for Evaluation

System	Evaluate	Rationale
Narrow Band Systems		
APCO P25 Phase 1	Yes	Mature technology that offers voice and data services that seem commensurate with the needs of A/G communications. 12.5 kHz channels would seem to offer capacity increase over current system.
APCO P25 Phase 2	No	This is a member of a class of systems that was eliminated from further consideration (Public Safety Radio—Narrowband—TDMA class) because the FDMA class was deemed more likely amenable to the communications problem, and because a custom development system (VDL Mode 3) essentially meets the classification parameters (VDL Mode 3 is a comparable system to the other members of the Public Safety Radio—Narrowband—TDMA class), provides substantially better capability, and was already being evaluated.
TETRA Release 1	No	This is a member of a class of systems that was eliminated from further consideration (Public Safety Radio—Narrowband—TDMA class) because the FDMA class was deemed more likely amenable to the communications problem, and because a custom development system (VDL Mode 3) essentially meets the classification parameters (VDL Mode 3 is a comparable system to the other members of the Public Safety Radio—Narrowband—TDMA class), provides substantially better capability, and was already being evaluated.
TETRAPOL	No	This is a part of the closely grouped set of Narrowband FDMA technologies (P25, TETRAPOL and EDACS). As discussed in section 3.4.2.1, P25 was evaluated as a representative member of this set.
IDRA	No	This is a member of a class of systems that was eliminated from further consideration (Public Safety Radio—Narrowband—TDMA class) because the FDMA class was deemed more likely amenable to the communications problem, and because a custom development system (VDL Mode 3) essentially meets the classification parameters (VDL Mode 3 is a comparable system to the other members of the Public Safety Radio—Narrowband—TDMA class), provides substantially better capability, and was already being evaluated.
IDEN™	No	This is a member of a class of systems that was eliminated from further consideration (Public Safety Radio—Narrowband—TDMA class) because the FDMA class was deemed more likely amenable to the communications problem, and because a custom development system (VDL Mode 3) essentially meets the classification parameters (VDL Mode 3 is a comparable system to the other members of the Public Safety Radio—Narrowband—TDMA class), provides substantially better capability, and was already being evaluated.
EDACS	No	This is a part of the closely grouped set of Narrowband FDMA technologies (P25, TETRAPOL and EDACS). As discussed in section 3.4.2.1, P25 was evaluated as a representative member of this set.
Wide-Band Systems		
APCO P34	Yes	Mature, robust data technology. TDMA guard bands are long, and MAC employs timing advance mechanisms. Scaleable physical layer and robust MAC layer.
Tetra Release 2—TAPS	No	Does not provide any known advantages over P34, and has a very small design range when compared to P34. P34 was selected for analysis as the most suitable technology in this class of technologies.
Tetra Release 2—TEDS	No	Does not provide any known advantages over P34, and has a very small design range when compared to P34. P34 was selected for analysis as the most suitable technology in this class of technologies.
Broad-Band Systems		
Project MESA	No	Project MESA is specifying requirements and identifying candidate technologies—standards not started. System is being designed to provide large data rates in small cells for incident specific applications. It is intended to supplement P25 and P34 networks, not replace them. Might provide a useful airport surface system, but insufficient detail is currently available to analyze the system.

3.4.3 Project 25 and Project 34 Technology Descriptions

Brief descriptions of APCO P25 and P34 are provided in the following sub-sections. These descriptions provide a basis for the technology evaluations. The description scope is limited to the set of information required to perform a pre-screening evaluation. Detail is provided on services provided, the technology functional architecture, and the technology air interface.

3.4.3.1 P25 Overview

APCO Project 25 is a digital FDMA trunked (with conventional non-trunked modes defined) radio specification with backward compatibility to traditional analog FM radios. The system is standardized through the EIA, and provides both digital voice and data communications in a variety of modes, with a variety of services. Modes include repeater (allows communications between a fixed station and a mobile

radio) and direct (mobile radio to mobile radio communications). The system is defined with open, standardized interfaces, so that manufacturers' equipment can be interoperable. It is the intent of the P25 specification that a system may be implemented where the equipment on either side of any open interface may be supplied by any manufacturer. The six open Project 25 interfaces that are defined are the:

- Air Interface (by convention this is designated as the *Um* interface, for example see fig. 3.4-3)
- 7. Data Peripheral Interface (by convention this is designated as the *A* interface)
- 8. Inter-System Interface (by convention this is designated as the *G* interface)
- 9. Network Management Interface (by convention this is designated as the *En* interface)
- 10. Data Interface (by convention this is designated as the *Ed* interface)
- 11. Interconnect Interface (by convention this is designated as the *Et* interface)

All of the interfaces are independent, as changes to one interface do not require changes to any other interface. A depiction of the P25 open system architecture is shown in figure 3.4-2.

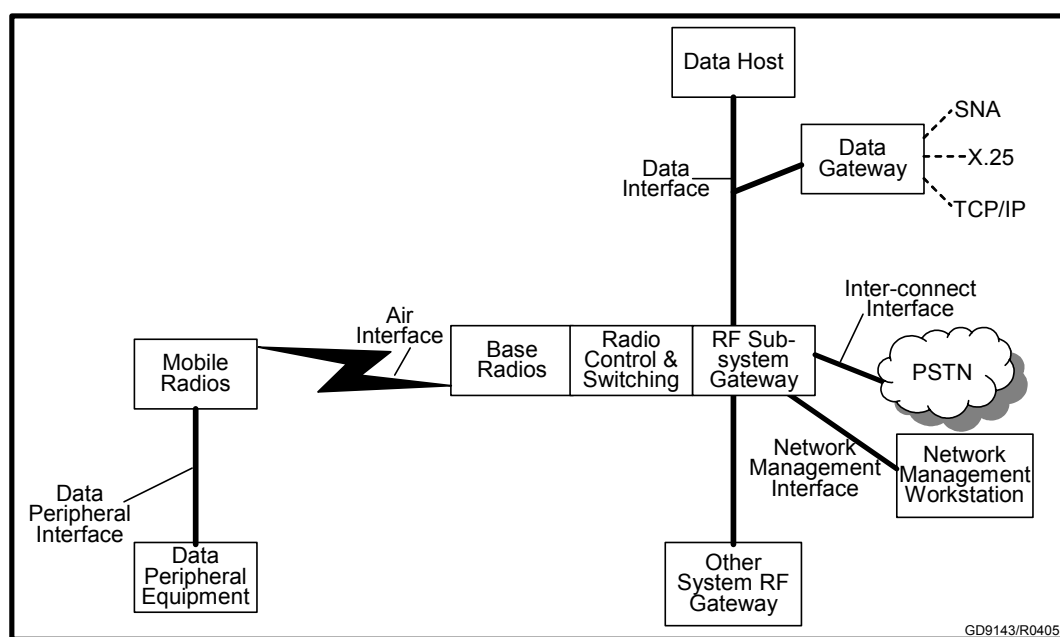
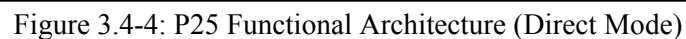
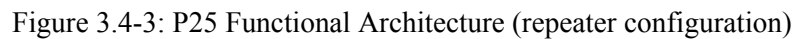


Figure 3.4-2: P25 Open System Architecture

3.4.3.1.1 P25 Functional Architecture

The P25 standards describe a general system model, or functional architecture, that is characterized by a number of functional groups and reference points (the EIA specification of P25 borrows the terminology coined by the CCITT for its specification of the ISDN). The two major P25 system configurations are the repeater mode and the direct mode configurations. Figure 3.4-3 shows the functional groups and reference points that are defined in a P25 system for the repeater mode of operation. Figure 3.4-4 shows the functions and reference points that are defined in a P25 system for the direct mode of operation. Specific functions in a functional group may or may not be present, depending on whether the system is being used in a conventional, trunked, or multi-station site configuration. The specific functions of a functional group may be performed in one or more pieces of equipment (the interfaces between functional groups

The P25 System definition document (TSB102-A) provides the following definitions for these functional groups:



NASA/CR—2005-213587

MRC (Mobile Router and Control): The mobile router and control functions group includes functions of voice and/or data routing, as well as control of the Mobile Radio (MR).

MR (Mobile Radio): The mobile radio functional group includes functions of transmission and reception of all RF signals.

BR (Base Radio): The base radio functional group includes only the functions of modulation and demodulation of the radio frequency energy. Elements within the BR include the power amplifier (PA), RF front end, IF selectivity, and end-IF detection device.

BA (Base Audio): The base radio audio and routing functional group includes the functions of frequency, level shaping and signal processing associated with the transmitted and received signals coupled to the BR.

BC (Base Control): The base radio control functional group includes the automated control functions of an individual base station.

RFC (Radio Frequency Control): The radio frequency control functional group include all logic for translating user-command signaling and control into base radio command signaling and control for one or more base stations. The RFC functions further include all logic for generating command signaling and control to a RFS functional group, if present.

RFS (Radio Frequency Switch): The radio frequency switch functional group functions include all switching for establishing interconnection paths between gateways and base stations, as directed, via command and control signaling from an RFC.

CON (Console): The console functional group functions include all end-system functionality for the dispatcher(s) including the dispatcher's Man Machine Interface (MMI), control, and audio functions.

MSC (Mobile Service Switching Center): The MSC is a switching center for services between radio sub-networks. The MSC is the combination of the RFC and RFS functional groups.

HLR (Home Location Register): The HLR is a dynamic data-base service which tracks the mobility of subscribers associated with a particular radio sub-network, and who roam to other radio sub-networks.

VLR (Visitor Location Register): The VLR is a dynamic data-base service which tracks the mobility of roaming subscribers which enter a radio sub-network, but who are associated with a different radio sub-network.

RFG (Radio Frequency Gateway): The radio frequency gateway functional group functions include direct interface with any/all end systems with the exception of the console (where the end system may be an RFG into another radio sub-system), and any translation of command signaling between the end system/user and the RFC. The RFG functions further include any translation of end system/user payload between the user and the RFS. The RFG also includes interface between VLRs, HLRs, and MSCs between RF subsystems.²⁶

3.4.3.1.2 P25 Services Provided and Key Features

The P25 and P34 standards classify services as either *bearer services*, *teleservices*, or *supplemental services*. The standard definitions of these services are provided below.

Bearer Services: Bearer Services are those telecommunications services which provide user information transport between network access points. These services are typified by lower-layer functionality, typically limited to OSI layers 1 through 3. The user may choose any set of high-layer protocols (layers 4 to 7) but the bearer service will not ascertain compatibility between users at these layers.²⁷

Teleservices: Those telecommunications services which provide complete facilities for transfer of user information, including terminal functions. These services are typified by both lower-layer (OSI layers 1 through 3) and higher-layer (OSI layer 4-7) functionality. Teleservices may be built on a named bearer service of the network or may require unique bearer capability which is not separately definable.²⁸

Supplemental Services: Those telecommunications services which modify or enhance the capabilities of a bearer service or a teleservice. Supplementary services cannot be offered alone. They must be associated with some other bearer or teleservice. The same supplementary service may be associated with several bearer or teleservices.²⁹

Table 3.4-4 shows the services that a P25 system can offer. Table 3.4-4 distinguishes between trunked and non-trunked systems, and indicates whether a particular service is a Standard Option, Mandatory, or Not Available.

Table 3.4-4: P25 Services, and Their Applicability to Trunked and Non-Trunked Systems

Telecommunications services		
<i>Bearer services</i>	<i>Non-trunked</i>	<i>Trunked</i>
Circuit switched unreliable data	Standard option	Standard option
Circuit switched reliable data	Standard option	Standard option
Packet switched confirmed delivery data	Standard option	Standard option
Packet switched unconfirmed delivery data	Standard option	Standard option
<i>Teleservices</i>	<i>Non-trunked</i>	<i>Trunked</i>
Broadcast voice call	Not available	Mandatory
Unaddressed voice call	Mandatory	Not available
Group voice call	Standard option	Mandatory
Individual voice call	Standard option	Mandatory
Circuit switched data network access	Standard option	Standard option
Packet switched data network access	Standard option	Standard option
Pre-programmed data messaging	Standard option	Standard option
<i>Supplementary services</i>	<i>Non-trunked</i>	<i>Trunked</i>
Encipherment	Standard option	Standard option
Priority call	Not available	Standard option
Pre-emptive priority call	Not available	Standard option
Call interrupt	Standard option	Standard option
Voice telephone interconnect	Standard option	Standard option
Discreet listening	Standard option	Standard option
Radio unit monitoring	Standard option	Standard option
Talking party identification	Standard option	Standard option
Call alerting	Standard option	Standard option
<i>Services to the subscriber</i>	<i>Non-trunked</i>	<i>Trunked</i>
Intra-system roaming	Standard option	Standard option
Inter-system roaming	Standard option	Standard option
Call restriction	Not available	Standard option
Affiliation	Not available	Standard option
Call routing	Not available	Standard option
Encipherment update	Standard option	Standard option

The P25 System definition document (TSB102-A) provides the following definitions for these services:

Circuit Switched Unreliable Data: A two-way data service between radio network access points providing a constant 9.6 kbps rate of information transfer with a (possibly) variable bit error rate. No

forward error correction or retransmission techniques are used. Service is accessible at reference points A and Ed.

Circuit Switched Reliable Data: *A two-way data service between radio network access points providing a bit error rate not to exceed 10^{-6} but with a (possibly) variable rate of information transfer. Forward error correction and/or retransmission techniques may be used. Service is connection oriented. Network resources are allocated on a call by call basis, (no sharing once a call/connection has been established). Service is accessible at reference points A and Ed.*

Packet Switched Confirmed Delivery Data: *A two-way data service between radio-network access points providing a variable rate of information transfer at BER not to exceed 10^{-6} . Multi-access channel sharing techniques are used to provide a service which maximizes the utilization of network resources for information transfers which are of a short burst nature. Error correction/protection services are provided by the radio network. Confirmation of delivery is provided. Service may be connection oriented or connectionless. Network resources are allocated on a shared basis among multiple calls or connections. Service is accessible at reference points A and Ed.*

Packet Switched Unconfirmed Delivery Data: *A two-way data service between radio network access points offering delivery of unconfirmed packets. Error correction and detection services can be provided by the network. Confirmed delivery is not provided, hence the service is inherently unreliable. Service is connectionless. Network resources are allocated on a shared basis among multiple calls or connections. Service is accessible at reference points A and Ed.*

Broadcast Voice Call: *This service provides one-way voice calls from an originating user to one or more other users. The target user group may be a subset of all of the system users or it may be all of the system users. The service is accessible at points C and B.*

Unaddressed Voice Call: *This Service provides two way voice calls from any user to an indefinite collection of one or more users. All parties within the coverage of the Unaddressed Voice Call can hear each other. The collection of users may be a subset of all the system users or it may be all of the system users, since the scope of the call is set by coverage, not addressing. The service is accessible at the points C and B. All parties in the group can hear each other. The group may be a subset of all of the system users or it may be all of the system users*

Group Voice Call: *This service provides two-way voice calls between one user and a predetermined group of users, of which the originating user is a member. All parties in the group can hear each other. The service is accessible at points C and B. The members of the group have one common, predefined number by which they are addressed. A terminal may be statically programmed for one or more groups or dynamically assigned by a dispatcher or system operator.*

Individual Voice Call: *This service provides two-way voice calls between one user and another individual user. The service is accessible at points C and B. Individual calls may be initiated by any user of the system. Calls may be placed to any other registered system user.*

Circuit Switched Data Network Access: *A two-way data service between user endpoints which provides wireless access to communications and value-added services supported by land-based circuit switched networks. The service is accessible at reference points A and Ed. Protocols at the reference points may be identical, in which case the mobile access point would appear to the user as functionally identical to the switched network access point. Alternatively, different low-layer protocols may be used at the two access points. This service would typically utilize a bearer service*

for transit through the radio system and would include additional gateway or interworking functions at both the subscriber and fixed terminations.

Packet Switched Data Network Access: *A two-way data service between user endpoints which provides wireless access to communications and value-added services supported by land-based packet switched networks. Service is provided between reference points A and Ed. Protocols at the reference points may be identical, in which case the mobile access point would appear to the user as functionally identical to the switched network access point. Alternatively, different low-layer protocols may be used at the two access points. This service would typically utilize a bearer service for transit through the radio system, and would include additional gateway or interworking functions at both the subscriber and fixed terminations.*

Pre-programmed Data Messaging: *A two-way data service providing delivery of fixed-meaning predetermined messages. Message meanings are agreed in advance and may be compressed to extremely small physical messages for actual transmission. The service is accessible at reference points B and C. This service would utilize a bearer service for transit through the radio system and would include additional terminal functions at both the subscriber and fixed terminations. This service is used to provide status signaling in dispatch applications.*

Encryption: *This service is supplementary to all bearer service and all teleservices. It provides for encryption of user information within the radio system. Encryption is not provided for information before it enters or after it leaves the radio system. The service is accessible at reference points A, B, C, Et, Ed and G. End-to-end encryption is only provided when both terminal devices are APCO Project 25 devices, which may be subscriber units or consoles. Encryption is provided end to end for calls across RF subsystem boundaries, but not for calls between terminals attached to a fixed network and interconnected to the radio network.*

Priority Call: *This service is supplementary to broadcast, group and individual calls. A call that has priority will be given preferential access to resources. If the required resources are unavailable (i.e. occupied by another user), a call with priority will be placed in queue ahead of all calls with lower priority. A minimum of five levels of priority are required. This service is accessible at reference points B and C.*

Preemptive Priority Call: *This service is supplementary to broadcast, group and individual calls. A call that has preemptive priority will always have resources allocated to it, even if this means that other calls will be disconnected. If the required resources are unavailable (i.e. occupied by another user), a call with preemptive priority will automatically cause the call with the lowest priority using such resources to be disconnected. The resources released will be given to the preemptive priority call. No action is needed by the user. A minimum of five levels of priority are required. This service is accessible at reference point B and optionally at point C.*

Call Interrupt *This service is supplementary to individual calls, but may interrupt any type of voice call; provided the individual is one of the call parties (it may not be possible to interrupt an individual while in a group call, unless that individual is the call originator). A dispatcher will be able to interrupt any call enabled by the system, by directing the call to the individual with the proper priority. The system may include the dispatcher, or may disconnect the third party in the call. The service is accessible at reference point B.*

Voice Telephone Interconnect: *This service is supplementary to broadcast, group and individual calls. This service allows calls between a telephone network user and one or more radio system users. It may be initiated from either the radio system side or the telephone network side. As an option, the*

system shall support full duplex telephone interconnect. The service is accessible at reference points B, C and Et.

Discreet Listening: This service is supplementary to broadcast calls, group calls and individual calls. It allows a user to selectively listen in on any call. That is, the user may select salient aspects of the call, such as group ID, to decide whether to listen or not. The service is accessible at reference point B and optionally at C.

Silent Emergency: This service is supplementary to broadcast calls, group calls and individual calls. The service causes a subscriber radio to initiate a call by itself, without the operator explicitly initiating the call by depressing the PTT switch (e.g. it may be initiated by the radio user pressing an emergency switch). The purpose of the service is to allow the dispatcher and/or other users to listen to activities at the site of the subscriber radio, in the event of possible danger to the radio user. The service is accessible at reference point C.

Radio Unit Monitoring: This service is supplementary to individual calls. The service causes a subscriber radio to initiate a call by itself, without the operator explicitly initiating the call by depressing the PTT switch, the call being initiated remotely by a radio dispatcher. The purpose of the service is to allow the dispatcher to listen to activities at the site of the subscriber radio, in the event of possible danger to the radio user. The service is accessible at reference point B.

Talking Party Identification: This service is supplementary to Broadcast calls, Group calls and Individual calls. This service provides the identification of the transmitting radio user at all of the receiving points. This service is accessible at reference points B and C.

Call Alerting: This service is supplementary to individual calls. This service provides the ability for the call originator to leave his identity with the called party for subsequent call back. The service operates only as a prompt for the called party to return the call. This service is accessible at reference points B and C.

Intra System Roaming: This service allows subscriber units to change their point of attachment within a radio system. The services available to the unit at the new point of attachment will depend on the service capabilities of the radio system. This service may be manual or automatic.

Inter System Roaming: This service allows subscriber units to obtain services from systems other than their home systems. The services available on the foreign system are subject to mutual system operator agreement. This service may be manual or automatic.

Call Restriction: This service allows the radio user to restrict the services which may be accessed from a specific radio at a specific time. This service may be initiated by the radio user or the system operator.

Affiliation: This service allows the subscriber to alter its affiliation status to other units within the system. This permits the subscriber to change from one talk group to another.

Call Routing: This service allows the user to use the system's capabilities to determine how to process a call in order to reach an intended target in a resource-efficient manner.

Encryption Update: This service allows the subscriber to obtain current encryption key information to support secure communications with appropriate targets. The service may be initiated by either the subscriber or the system.³⁰

Figure 3.4-5 shows the P25 air and data interfaces for the repeater mode or configuration. The air interface is precisely the same in the direct (mobile radio to mobile radio) mode, and consists of an IP network layer over the layer 2 and layer 1 common air interface for data transport, and an DVSI IMBE vocoder directly interfacing with layer 2 and layer 1 for voice transport.



The P25 MAC provides access to the radio channel in such a way as to minimize collisions between data messages from different subscriber units, and also to minimize collisions between data and voice. The technique of Carrier Sense Multiple Access (CSMA) is used for this purpose. On typical repeater channels, there is a radio frequency pair. One frequency is used for inbound messages to the repeater's receiver and another frequency is used for outbound messages from the repeater's transmitter. The repeater is full-duplex, so it can transmit simultaneously while it is receiving. While the repeater is transmitting, it can send status information to all the listening subscriber units about the status (idle or busy) of the inbound channel. When a subscriber unit wishes to transmit a data message, it generally waits until the inbound channel is idle before it transmits.

66

(typically at least 5). In a trunked system, two types of channels are defined, traffic and control channels. Control channels are used for signaling and broadcast of system information, and traffic channels are used for transmission of digitized voice and packet data.

In the trunked mode, subscriber units are required to acquire and lock to the control channel, which they then continuously monitor for control words. Typical actions in this state are to either “Go to a Traffic Channel,” which is initiated to enable reception of inbound messages, or if an inbound service packet (ISP) is required to be sent (for instance, the user has a request to send data), the radio waits for an inbound slot on the control channel, and then transmits the inbound service packet. The subscriber units use a slotted Aloha technique to send ISPs on the control channel. The slot boundaries for a trunking control channel are set by the status symbols in the outbound messages. The status symbols occur every 7.5 ms. A nominal slot structure is defined in the specifications³¹ for this purpose that provides a radius of coverage distance of 40 miles. The specification carefully uses the word nominally, with an inference that the actual distance and corresponding propagation guard time can be adjusted as required.

Both voice and data are sent over the air through the traffic channel as data units. Each data unit is preceded by a Frame Sync and a NID. Frame Sync is used by the receiver to locate the first bit of the data unit. The NID is used to identify the system and the type of data unit. A Link Control Word, is used to carry system signaling and information on the traffic channel.

Conventional systems can be classed as either repeater systems or direct systems. Repeater systems make use of a full duplex base station that is configured so that all of the signals that are received are re-transmitted. Direct systems simply transmit directly from one unit to another without the assistance of any intervening repeater. Radio units in a system consist of mobile and base stations. It is envisioned that the applicability of P25 to aeronautical A/G communications would be in the direct base-station to mobile-radio conventional mode of operation. In this mode of operation, the channel access protocols are very simple. Voice is the listen before push-to-talk protocol, and data transmission is initiated when no channel activity is detected.

3.4.3.1.4 P25 Standards

The P25 standards occupy some 34 volumes and completely specify the six open interfaces of the system. The standards are mature and complete.

3.4.3.2 P34 Overview

P34 is a wideband Public Safety digital radio system that provides high-speed packet data services using the Internet Protocol on 50, 100, and 150 kHz channels in the 700 MHz band. P34 systems provide connectivity between Mobile Radios and Fixed Network Equipment (FNE), Mobile Radios to Repeaters to Mobile Radios, and direct Radio to Radio (either mobile or fixed) connectivity.

The objectives stated in the Project 25/34 (the official name of P34 was Project 25/34) Statement of Requirements (SOR) are [bolding added for emphasis]:

*...establish, from the user's perspective, a standards profile for the operation and functionality of new **aeronautical** and terrestrial wireless digital wideband public safety radio standards that can be used for the transmission and reception of voice, video, and high speed data in a ubiquitous, wide-area, multiple agency network. Some of the primary attributes of this network(s) would include, but not be limited to, the following:*

B. Affords immediate, significant and evolutionary improvements in radio bandwidth and spectrum efficiency.

F. Establishes a digital tactical communications architecture that provides for a “migration-in-place” transition within existing systems, effected through full backward interoperability/compatibility with existing analog and digital wireless communications systems used by local, state and federal agencies.

G. Is consistent with Project 25 Phase I and Phase II and parallel federal standards.

I. Allows for the half and/or full duplex transmission of digital information at gross channel data rates of up to a minimum of 1.544 megabits per second (Mbits/s, 3rd generation), and 155 Mbits/s or higher for 4th generation technologies.

J. Allows for the seamless hand off of subscriber units moving between fixed sites.

*K. Allow for multiple levels of security, network integrity, and availability.*³²

APCO Project 34 is standardized through the EIA. An offshoot of Project 25, this project addressed wideband aeronautical and terrestrial mobile digital radio technology standards for the wireless transport of rate-intensive information. The project committee discovered four generally universal limitations restricting the use of commercial services for mission-critical public safety wireless applications:

- Priority access and system restoration
- Reliability
- Ubiquitous coverage
- Security

P34 describes a platform that can be installed as a government/ commercial partnership that overcomes these limitations and provides universal access to all subscribers within a carefully controlled and managed network. It establishes standards for the transmission and reception of voice, video and high-speed data in a wide-area, multiple-agency network.

The P34 system is defined with open, standardized interfaces, so that manufacturers' equipment can be interoperable. It is the intent of the P34 specification that a system may be implemented where the equipment on either side of any open interface may be supplied by any manufacturer. The three open interfaces that are defined are the:

1. Wideband Air Interface (U_w)
2. Data Peripheral Interface (Mobile Data Peripheral to Mobile Radio Control, A_w)
3. Data Interface (Radio Frequency Gateway to Data End System, E_w)

A depiction of the P34 open system architecture is shown in Figure 3.4-6.

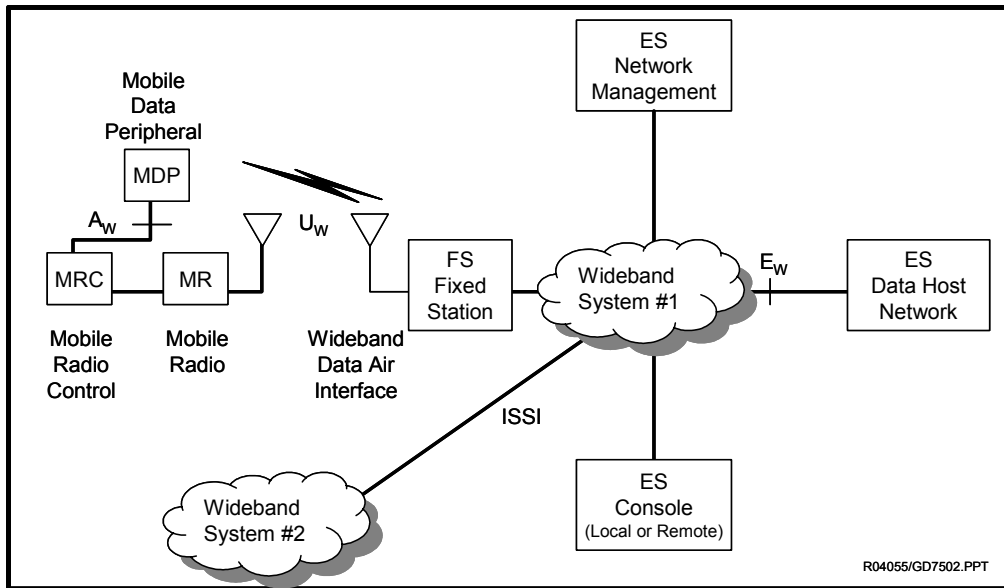


Figure 3.4-6: P34 Functional Architecture

3.4.3.2.1 P34 Functional Architecture

As might be expected, the functional groups defined for Project 34 standards show heavy reuse from the Project 25 standards. The defined functional groups include the mobile radio, mobile routing and control, mobile data peripheral, base radio, base routing and control and radio frequency gateway. These functional groups have the same interrelationship and definitions as previously described in the Project 25 functional architecture section.

3.4.3.2.2 P34 Services Provided and Key Features

The P34 system is specified to provide IPv4 and IPv6 bearer services for the transport of packet data using the IP suite of protocols. The wideband IPv4 (and IPv6) delivery service is required to directly support standard IP transport layers, including UDP, TCP and RTP. It may optionally transport other protocols via standard IETF encapsulation methods. Unicast service is required, and broadcast and multicast services are standard options. Utilization of Mobile IP and IPsec services may be optionally implemented.

The P34 supplemental services include security, data compression, streaming audio transport and streaming video transport. The following descriptions of these services apply:

Security: The wideband data suite should include capabilities for packet integrity, confidentiality and user/radio authentication

Data Compression: The wideband data suite should include capabilities for both IP header and user data compression.

Streaming Audio Transport: The wideband data suite should include capabilities for standard Internet streaming audio services.

Streaming Video Transport: The wideband data suite should include capabilities for standard Internet streaming video services.

3.4.3.2.3 P34 Air Interface Description: PHY, MAC and Network

Figure 3.4-7 shows the P34 air and data interfaces for the mobile radio to fixed network equipment configuration. The air interface is precisely the same in the direct (mobile radio to mobile radio) mode, and consists of an IP network layer over the layer 2 and layer 1 common air interface for data transport.

P34 has two defined physical layers. One is required (Scalable Adaptive Modulation, SAM) for interoperability, whereas the optional physical layer (Isotropic Orthogonal Transform Algorithm, IOTA) is provided for increased capacity. Both physical layers define adaptive signal constellations on an Orthogonal Frequency Division Multiplexed (OFDM) set of carriers. SAM uses QPSK, 16QAM or 64QAM as channel conditions warrant. IOTA uses an Amplitude Shift Keyed modulation format, with 2-ASK, 4-ASK and 8-ASK signal constellations. Both physical layers are defined with a base implementation on a 50 kHz channel, using modulation parameters and frames that simply scale to provide the required 100 and 150 kHz channel bandwidths. Table 3.4-5 shows the modulation parameters for SAM. Clearly, all of the parameters stay the same, with the notable exception of the number of RF carriers (called subchannels in the table), which scales. This provides a very robust mechanism whereby the time domain frame is also scaled by repetition (the same basic structure is used once in the 50 kHz system, twice in the 100 kHz and three times in the 150 kHz) and the extra bits are now mapped to the extra carriers.

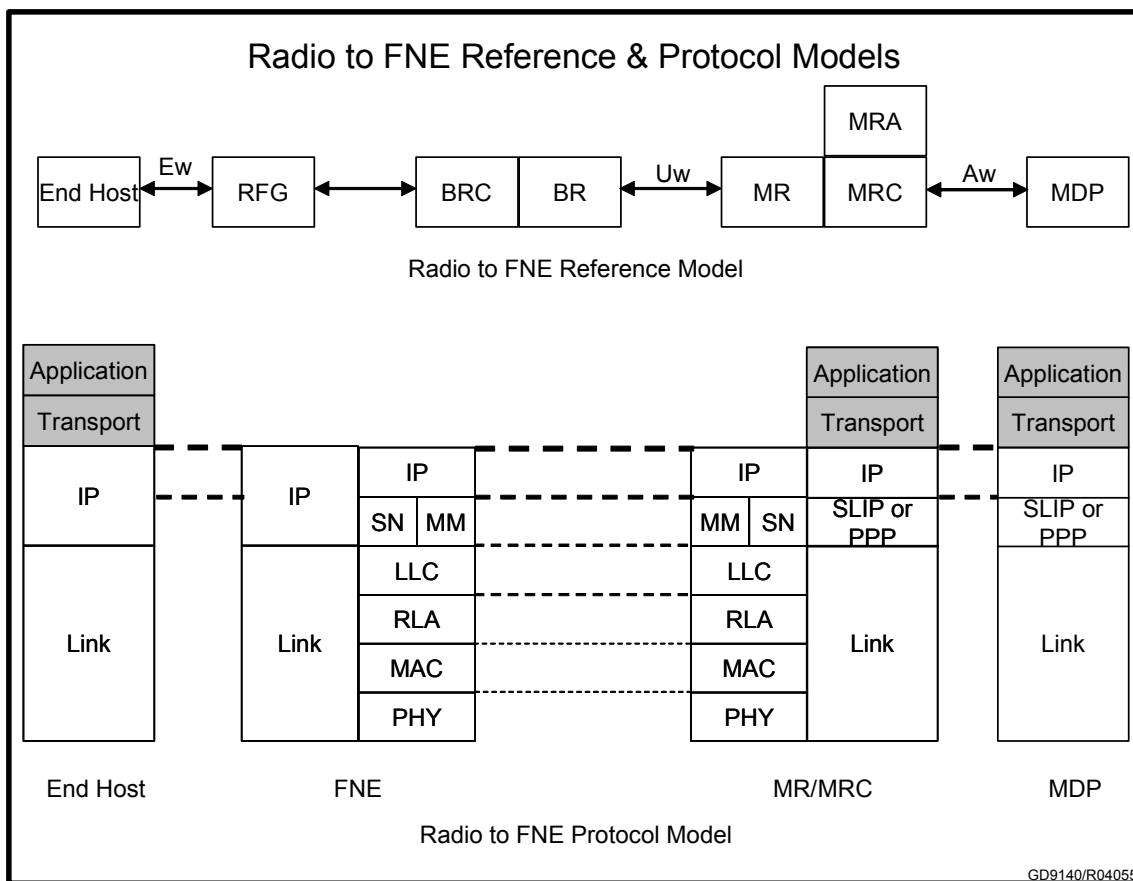


Figure 3.4-7: P34 Radio to Fixed Network Equipment Reference and Protocol Models

Table 3.4-5: Scaleable Adaptive Modulation Parameters

Parameter	50 kHz Channel Configuration	100 kHz Channel Configuration	150 kHz Channel Configuration
RF Subchannels	8	16	24
Subchannel Spacing	5.4 kHz	5.4 kHz	5.4 kHz
Symbol Rate	4.8 k	4.8 k	4.8 k
Symbol Filter	Root Raised Cosine ($\alpha = 0.2$)	Root Raised Cosine ($\alpha = 0.2$)	Root Raised Cosine ($\alpha = 0.2$)
Modulation Type 1	QPSK (2 bits/symbol)	QPSK (2 bits/symbol)	QPSK (2 bits/symbol)
Modulation Type 2	16QAM (4 bits/symbol)	16QAM (4 bits/symbol)	16QAM (4 bits/symbol)
Modulation Type 3	64QAM (6 bits/symbol)	64QAM (6 bits/symbol)	64QAM (6 bits/symbol)
Modulation Rate 1	76.8 kbps	153.6 kbps	230.4 kbps
Modulation Rate 2	153.6 kbps	307.2 kbps	460.8 kbps
Modulation Rate 3	230.4 kbps	460.8 kbps	691.2 kbps
Demodulation	Coherent (Pilot Symbol Assisted)	Coherent (Pilot Symbol Assisted)	Coherent (Pilot Symbol Assisted)
TDM Slot Time	10 ms	10 ms	10 ms
Slot Interleave	Variable	Variable	Variable

The expected performance of this modulation in the A/G channel is quite good. Rather than using the typical cyclic prefix that is common to most OFDM systems, both SAM and IOTA implement coherent detection by transmitting a number of pilot symbols in every frame. Each pilot symbol transmits a known phase and amplitude value to the receiver. From this, the receiver can determine the amplitude and phase distortion of the channel, and apply the inverse function to reconstruct the symbol. This technique provides immunity to delay spread as long as the coherence time of the channel is long compared to the symbol duration.

An estimate of channel coherence time can be formulated from the Doppler spread of the channel (they are inversely proportional). The Doppler spread associated with the A/G communications channel can be estimated and compared to the symbol rate, to judge the immunity of this waveform to Doppler spread. Before discussing this however, it is illustrative to recall the assumptions used to create the classic Jakes Doppler power spectrum. The derivation of the spectrum assumes envelope detection and a uniform distribution of azimuthal angles of arrival. This latter assumption provides a nice approximation for an urban canyon; however, it isn't likely that an aircraft in flight would have angles of arrival that came anywhere near this approximation. Most authors in describing the A/G channel use a two-ray model. Such a model has a bimodal Doppler distribution. Regardless, the worst case assumption of uniform angles of arrivals results in some useful approximations that can be made about the Doppler spread that is expected for the A/G channel. In a study conducted for Eurocontrol, investigations into the feasibility of UMTS for Air Traffic Control focused on modeling the small-scale fading effects of the A/G channel. Figure 3.4-8 presents the results of their simulations.

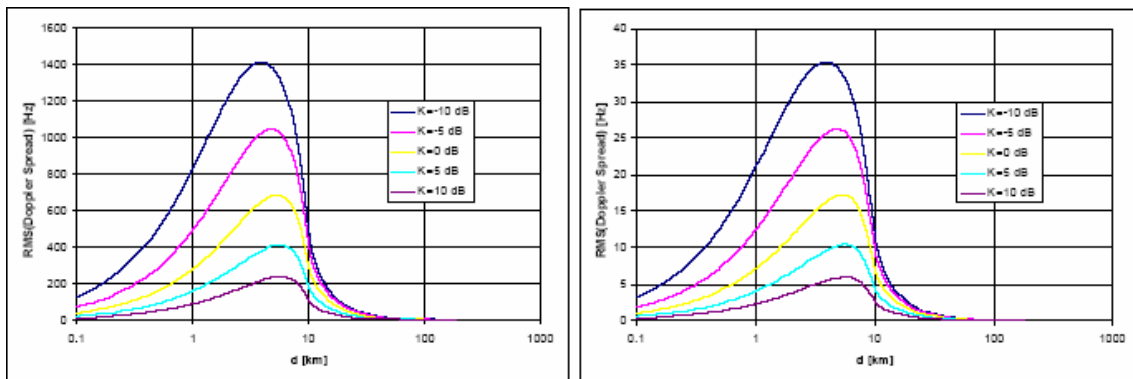


Figure 3.4-8: Simulated RMS Doppler spread for C band and VHF.

Left figure is computed with frequency of 5.1 GHz (C band); Right figure with a frequency of 128 MHz (VHF)³³

The authors draw the following observations from their simulations:

- As the Rician K factor increases, the RMS Doppler spread decreases. This effect is significant, since the Doppler spread decreases by half of its maximum value when K goes from -10 dB to 0 dB.
- The Doppler spread is very small at large distance from the airport, and increases as the plane enters in the scattering circle. Again, it is expected that the model largely over-estimates this effect. As the plane gets closer to the airport, the RMS Doppler spread decreases, since the LOS component received by the airport antenna is mostly dominant.
- Finally, the impact of the Doppler spread at VHF is extremely small compared with the computed Doppler spread at C band. For instance, the maximum RMS Doppler spread at VHF is about 40 Hz, as compared to 1,500 Hz at C band with K = -10 dB. Nevertheless, the maximum computed RMS Doppler spread is about 700 Hz for a Rician K factor equal or above 0 dB in C band and decreases to less than 250 Hz if K = 10 dB.³⁴

The P34 signaling rate of 4800 symbols/second is sufficiently high that the Doppler spread predicted for the A/G channel should not be an issue. Were this not the case, or if the Doppler spread is somehow larger than we might expect, significant work has been done to characterize the effects on OFDM, and most authors report that the effect of large Doppler Spread on an OFDM system is proportional to the number of carriers in that system. Since the P34 physical layer uses a maximum of 24 carriers (as compared to hundreds or even thousands in other OFDM systems) P34 should be fairly robust to inter-carrier interference that is caused by large Doppler spreads. A useful result of an analysis of OFDM is quoted below:

In this paper, we have first investigated the effect of the number of carriers (N) and the guard time duration (ν) on the performance of an OFDM system operating on a frequency selective time-selective fading channel. Our main conclusions are the following.

- *For short frames, the time-selectivity of the channel can be ignored. The frequency-selectivity of the channel yields equal portions of ISI and ICI. The total interference power decreases with ν and is proportional to $1/N$.*
- *For long frames, the frequency-selectivity of the channel can be ignored. The time-selectivity of the channel yields ICI but no ISI. The ICI power does not depend on ν and increases with N .*³⁵

The P34 MAC provides the following functions:

- Logical channel management and synchronization
 - Random Access Channel
 - Broadcast Control Channel
 - Slot Signaling Channel
 - Packet Data Channel
- Channel access, allocation of bandwidth, and contention resolution
 - Priority queuing
 - Slotted-Aloha reservation requests
 - Carrier sense multiple access for direct mode (mobile to mobile)
- Dynamic radio link adaptation control
- Radio power management
 - Uses both closed and open-loop power control
- Radio channel encryption and scrambling

The P34 MAC layer priority queuing and slotted Aloha reservation request functions are accommodated via inbound random access slot structures. This slot structure limits the design range of a P34 system to 187.5 km for SAM and 150 km for IOTA. However, the design range would appear to be easy to modify by requiring that only the even (or odd) reservation slots be used when making reservation requests for data. The P34 standard defines three slot structures:

- Outbound—continuous stream of 10 ms slots
- Random Access Inbound—500 μ s guard and 500 μ s ramp-down for IOTA, 625 μ s guard and 208.33 μ s ramp-down for SAM
- Scheduled Inbound—0 μ s guard and 500 μ s ramp-down for IOTA, 208.33 μ s guard and 208.33 μ s ramp-down for SAM

The P34 MAC layer implements a timing advance that assures propagation delays are not seen at the radio receiver except for the initial random access slot. Figure 3.4-9 shows the P34 slot structure. Each standard 10ms slot is partitioned into two random access data slots (note that a 50 kHz system has only one frame or slot structure, whereas the 100 kHz system has two, and the 150 kHz system has the three slot structure that is shown in the figure). The figure is color coded to show the notional increase in guard band that could be provided if only the even reservation slots were allowed to be used (colored green) and the odd slots (colored red) were not utilized. (Note that the drawing is not to scale.)

AGC Preamble	Inbound Random Access Subslot #1 Data	Propagation Delay	AGC Preamble	Inbound Random Access Subslot #2 Data	Propagation Delay
AGC Preamble	Inbound Random Access Subslot #3 Data	Propagation Delay	AGC Preamble	Inbound Random Access Subslot #4 Data	Propagation Delay
AGC Preamble	Inbound Random Access Subslot #5 Data	Propagation Delay	AGC Preamble	Inbound Random Access Subslot #6 Data	Propagation Delay

Figure 3.4-9: P34 Slot Structure (150 kHz System shown)

3.4.3.2.4 P34 Standards

The P34 standards are complete, with the exception of TIA-902.AAAB (Text Messaging Service), which is still in drafting, and TIA-902.CBAA (IOTA Transceiver Method of Measurement) and TIA-902.CBAB (IOTA Transceiver Performance Recommendation) which are also still in drafting. The SAM modulation is completely specified with published specifications for the physical layer, the MAC, link layer control and mobility management, as well as the method of measurement and transceiver performance standards. Figure 3.4-10 shows the status of the P34 standards.

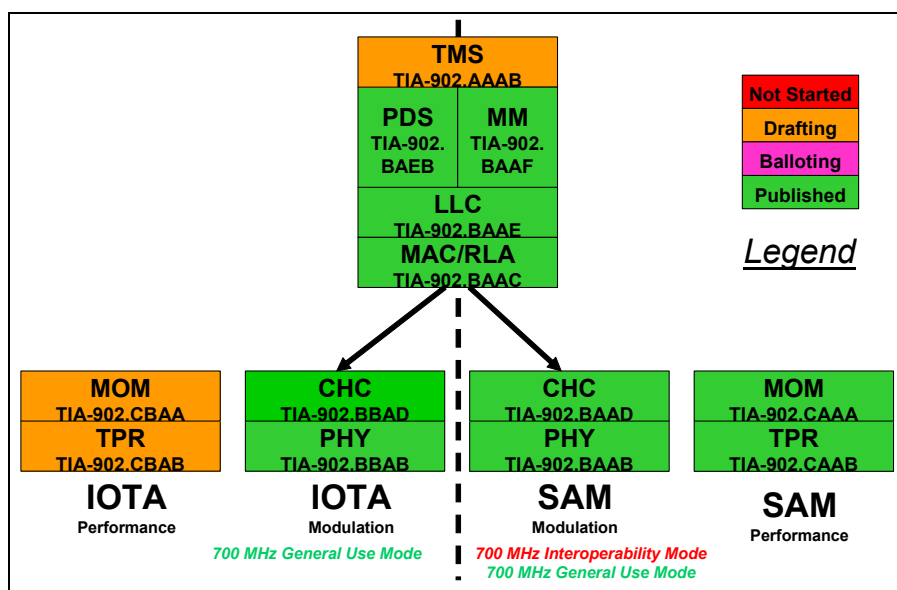


Figure 3.4-10: P34 Standards Status

3.4.4 Concept of Use: Application to Aeronautical A/G Communications

This section describes the application of APCO Project 25 and Project 34 to aeronautical communications, which provides the basis for subsequent evaluation. This concept of use description involves the following elements:

- Applicable Frequency Band: the band or bands that are appropriate for the implementation of APCO Project 25 and Project 34 for aeronautical communications
- Applicable Airspace: the airspaces in which APCO Project 25 and Project 34 can practically provide aeronautical communications
- Services Used: the APCO Project 25 and Project 34 services that are best applicable to aeronautical communications
- Architecture Integration: description of how the APCO Project 25 and Project 34 architecture integrates into the architecture for aeronautical communications.

Each of these is, in turn discussed below.

3.4.4.1 P25 Concept of Use

3.4.4.1.1 General Discussion

P25 systems can be deployed as either conventional or trunked. The system architecture can be either repeater or direct mode. Repeater systems are further classified as simple or fixed network configurations. Each of these configurations and modes have some merit, and depending on the mode selected, the ability of a P25 system to provide future aeronautical communications changes, and its evaluation changes to reflect this. The following paragraphs provide a basis for the reference configuration and mode that was selected as a basis for the P25 evaluation.

Trunking. The most effective use of this technology is a trunked configuration; however, it is recognized that some certification issues with Grade of Service traffic engineering would most assuredly result in a requirement for one dedicated frequency per controller. It is expected that if a trunked mode was implemented, a set of frequencies would be assigned that provided at least one frequency for every controller (dedicated voice), and additional frequencies (not necessarily one for every controller) for data.

Trunked operation requires a Trunking control channel. In P25 systems, the Trunking control channel is required to be full duplex. (Note that only the base station radio is required to work in a duplex mode however. The mobile radios can all be half-duplex, and in practice, this is usually the case.) The control channel can be allocated for voice and data, but this is only recommended for lightly loaded systems. The consequences of this type of configuration would be that the P25 system would not be able to provide a notional doubling of frequency assignments if it were deployed in a Trunking configuration. Clearly, some additional capacity (assignable circuits) would accrue from the reduced channel separation; however, the assignment of full-duplex Trunking control circuits would reduce the pool of circuits that could be allocated to voice.

Conventional. While voice and data can be shared on a common channel with a P25 system, there is no accommodation for rigorously segregating the two types of traffic. Stated differently, a P25 channel can accommodate either a voice packet or a data packet at any given time. P25 system planning documentation recommends that the number of users be kept to less than 20 per frequency if voice and data is to be used on the same frequency. The provisioning of a data link for conventional mode would either rely on contention based sharing of the channel between voice and data (this is envisioned to create certification difficulties) or by a separate channel assignment for voice and data.

Dual Mode. Perhaps the most effective application of this technology for A/G aeronautical communications would be conventional (single frequency) mode for voice communications, and a trunked mode for data communications. The end-to-end data communications requirements of ATSC Class B traffic could very likely be met by a trunked data system of say, five channels, even on a busy airport surface. Applying the technology in this fashion would not provide the additional voice capacity required however.

In addition to a decision between conventional and trunked modes of operation, a decision is required between direct and repeater modes base station operation. The repeater mode requires the allocation of a frequency pair for each base station. This would not meet the spectral efficiency requirements of doubling the assignable channels. Furthermore, the direct mode of operation is more aligned with the current A/G communications infrastructure than the repeater mode, so it is envisioned that the applicability of P25 to aeronautical A/G communications would be in the direct base-station to mobile-radio.

From the preceding discussion, the following is an appropriate application of this technology to A/G communications:

- P25 systems would be deployed using conventional, direct-modes between a base station radio and the mobile radios
- Data communications would share the assigned voice circuits on a contention basis. This impacts the system capability to provide QoS. Data throughput and data latency are also degraded. However, this is the only way to achieve the doubling of assignable voice channels.

Clearly, the specified configuration is primarily a voice system. It provides some data, but not in a guaranteed or timely fashion.

3.4.4.1.2 Applicable Frequency Band

P25 systems would be deployed in the VHF band. The current channelization of the band would have to be reduced to 12.5 kHz to accommodate this technology.

3.4.4.1.3 Applicable Airspace Environments and Aeronautical Communications Services Provided

The use of P25 systems would provide A/G communications in continental airspace, which includes en-route, terminal and surface communications, but excludes oceanic and polar communications. Additionally, air-to-air communications would be provided in all regions by these technologies. The Aeronautical Communications Services that could be provided by P25 include:

- Pilot-Controller Voice: group conference, addressed, and broadcast
- A/G and G/A addressed data
- G/A broadcast data
- Direct A/A communications

3.4.4.1.4 Applicable P25 Services

The following P25 services would be used to provide the required Aeronautical Communications Services:

- P25 Teleservices
 - Broadcast Voice Call (voice broadcast function)
 - Unaddressed Voice Call (controller-pilot group conference call)
 - Individual Voice Call (controller-pilot selective addressed voice)
 - Circuit Switched Data Network Access

- Packet Switched Data Network Access
- Pre-programmed Data Messaging
- P25 Supplemental Services
 - Call Interrupt
 - Talking Party Identification
 - Encryption
 - Silent Emergency
 - Radio Unit Monitoring

The definitions of these services were provided in section 3.4.3.1.2.

3.4.4.1.5 Architecture Integration

The P25 system would map to aeronautical control sites, radio sites and avionics as shown in figure 3.4-11.

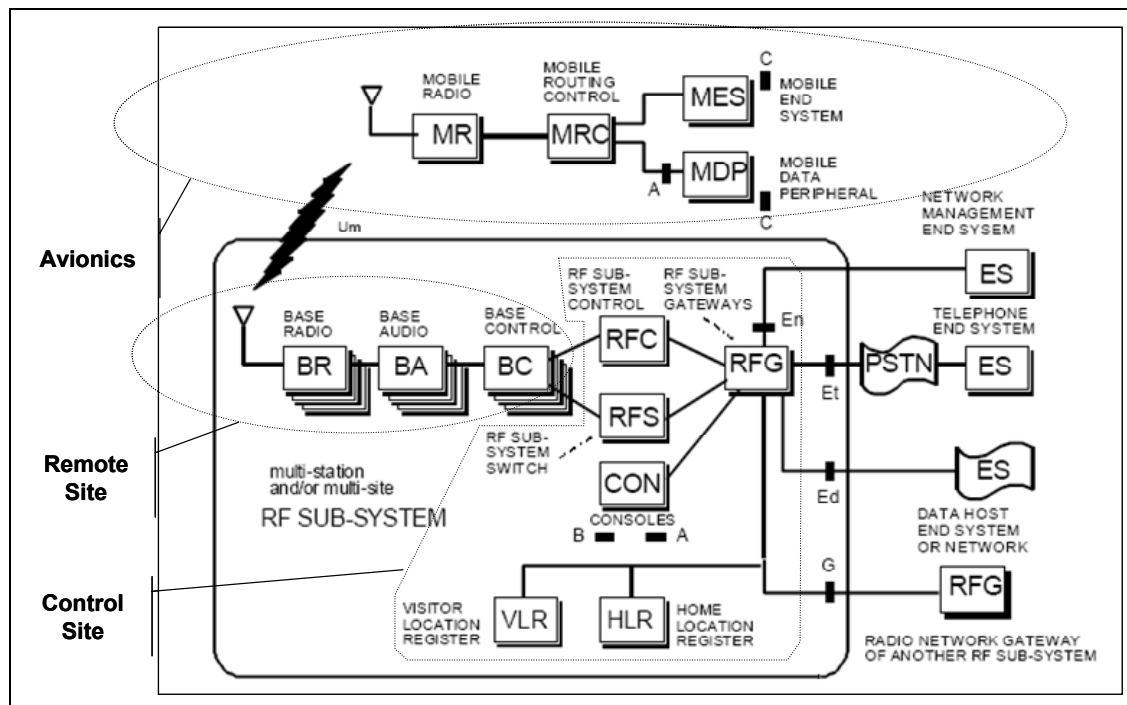


Figure 3-4.11: Mapping of P25 Functional Architecture to a Physical System Architecture

For the ground infrastructure, figure 3.4-12 shows the allocation of P25 functions to ground radios, radio control equipment, voice switches and a notional ATN gateway and application.

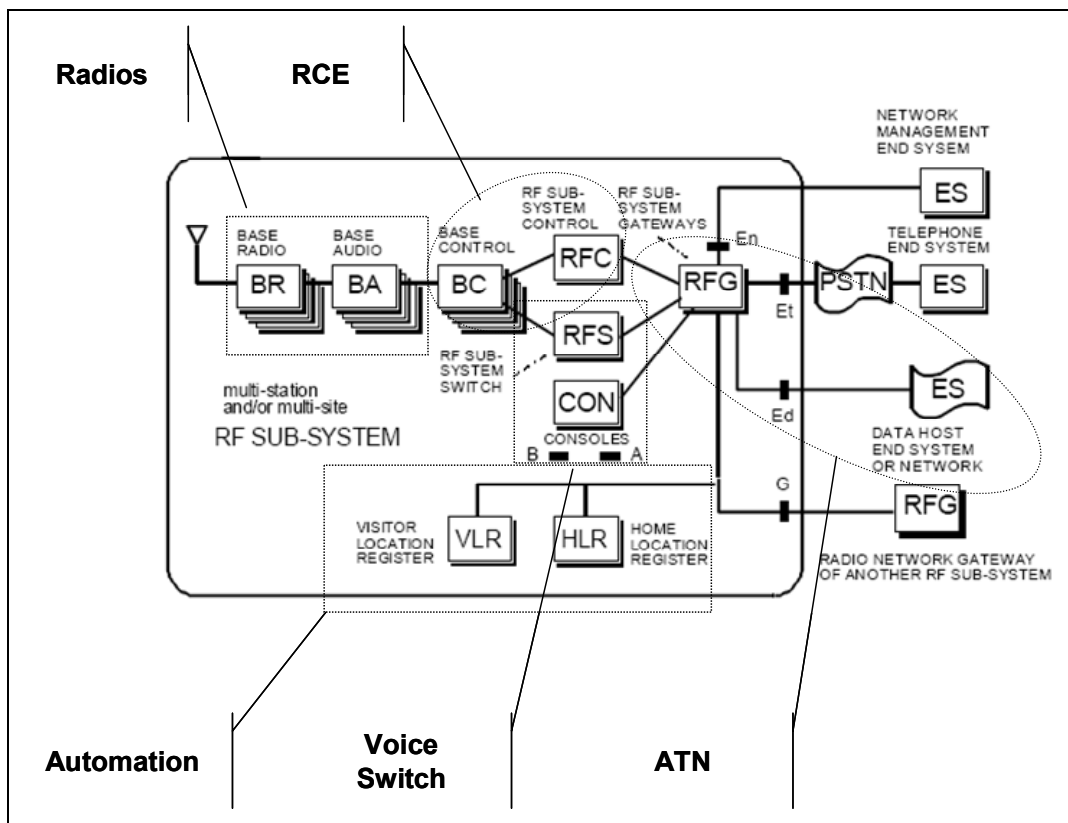


Figure 3.4-12: P25 Ground Infrastructure

3.4.4.2 P34 Concept of Use

As has been mentioned previously, some modifications to the P34 standards would be required to accommodate the long ranges required for A/G communications. Current P34 specifications would accommodate sectors up to 187.5 km in extent. Modifications to the channel random access protocol seem straightforward, and would enable the provisioning of large sectors.

3.4.4.2.1 Applicable Frequency Band

P34 systems could be deployed in the DME band (960 to 1024 MHz) which already has an Aeronautical Radio-navigation allocation. Use of this band would be subject to WRC approval of co-prime allocation to AM(R)S.. Additionally, a new channelization scheme would have to be provided in the band, to accommodate the P34 system's use of 50, 100, and 150 kHz channels. A notional channelization scheme is provided in figure 3.4-13.

As can be seen in the figure, the P34 base stations would be full-duplex. The P34 mobile radios would operate in a half-duplex mode. Communications between the aircraft (mobile radios) and the ground (base stations, or more precisely fixed network equipment) would follow the P34 "Mobile Radio to Fixed Network Equipment" process. Communications between aircraft would be in accordance with the P34 "Radio to Radio" configuration. This is the most basic of P34 configurations, and is frequently called *talk-around* in the literature. Both modes would be supported by the same avionics radio.

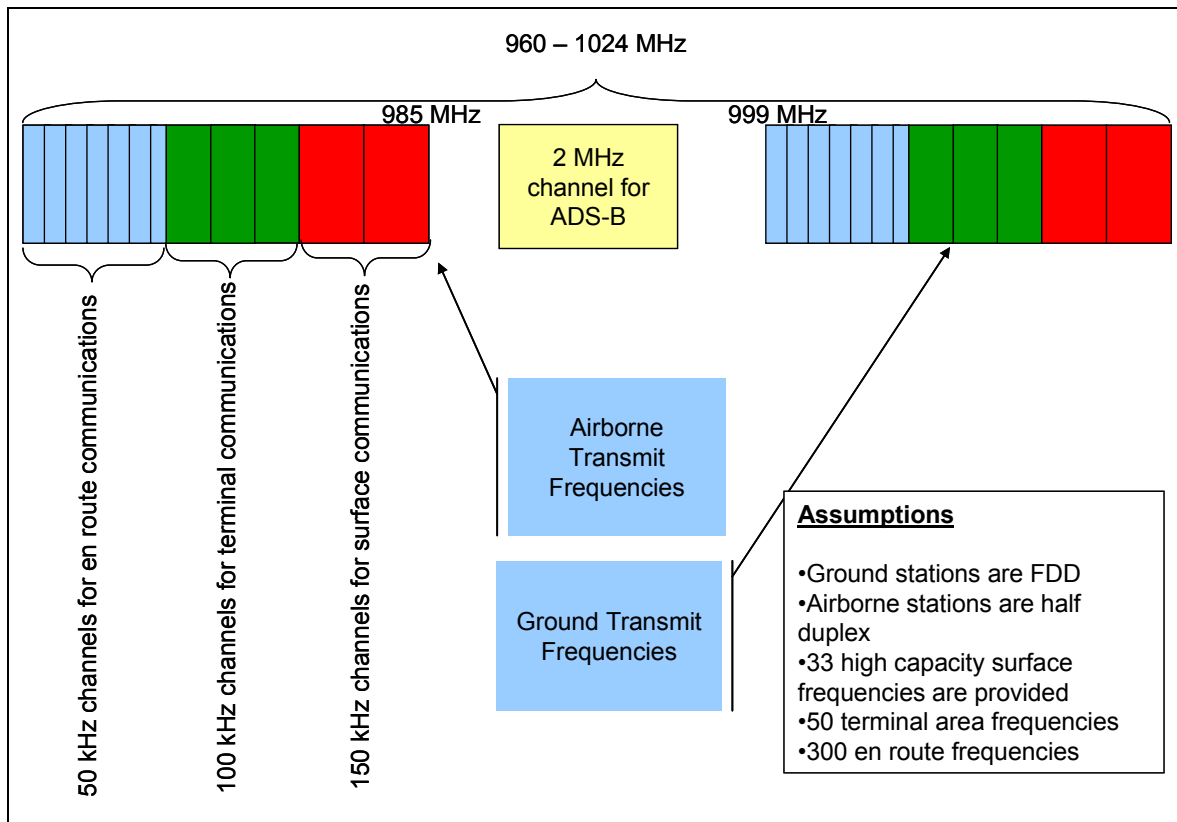


Figure 3.4-13: Notional DME Band Channelization to Accommodate P34

3.4.4.2.2 *Applicable Airspace Environments and Aeronautical Communications Services Provided*

The use of P34 systems would provide A/G communications in continental airspace, which includes en-route, terminal and surface communications, but excludes oceanic and polar communications. Additionally, air-to-air communications would be provided in all regions by these technologies. The Aeronautical Communications Services that could be provided by P34 include:

- Pilot-Controller Voice: group conference, addressed, and broadcast
- A/G and G/A addressed data
- G/A broadcast data
- Direct A/A communications

P34 is a packet data protocol. Voice transport over P34 would necessitate the use of Voice over Internet Protocol (VoIP). Talk groups would be set up using multicast IP services, and individual voice calls would be set up using unicast IP services. Most of the voice requirements could be met by P34, even though its primary intent was for delivery of high speed data. Air-to-air data services and ground-to-air data services are native modes of the technology. Provisioning ADS-B with P34 would be somewhat problematic because of the size of the P34 random access slot. P34 defines a random access slot of 5 ms duration. This means that a 50 kHz P34 system could provide no more than 200 random access opportunities for broadcast of ADS-B position reports a second. Each slot provides 262 bits of useable (payload) data, as the specification requires that the random access slots use the lowest modulation symbol constellation (the IOTA physical would thus use 2-ASK and provide 262 bits; SAM uses QPSK and provides somewhat less, roughly 164 bits). When compared with the UAT, which offers 3200 message start opportunities every second, each providing the ability to send either a 16 or 32 byte ADS-B message, the following observations can be made:

- IOTA physical layer looks like a better match than the SAM physical layer for transfer of ADS-B message (provides the same data message transport size as UAT)
- In order to provide the same number of message opportunities, the P34 system would have to be scaled sixteen-fold. This represents a system with a signal bandwidth of (16*50 kHz) 800 kHz, which compares favorably with the UAT
- As the modulation is defined to scale linearly, this seems to be achievable. However, this signal would require a large number of subcarriers (roughly 397 for IOTA and 128 for SAM), and its performance in the A/G channel needs to be evaluated carefully.

3.4.4.2.3 *Applicable P34 Services*

The P34 services that would be used to provide A/G communications include:

- Unicast IPv4 and IPv6
- Broadcast IPv4 and IPv6
- Multicast IPv4 and IPv6
- Security Services
- Mobility Management

3.4.4.2.4 *Architecture Integration*

Figure 3.4-14 provides a notional view of the avionics required for a P34 implementation of ADS-B and AOC and ATS functions. The P34 ground infrastructure could be provided with the same physical components as P25, or it can be substantially simplified. Since the P34 network layer is IP, implementation of most of the switching, control, mobility management and security functions could be accomplished with commercially available routers.

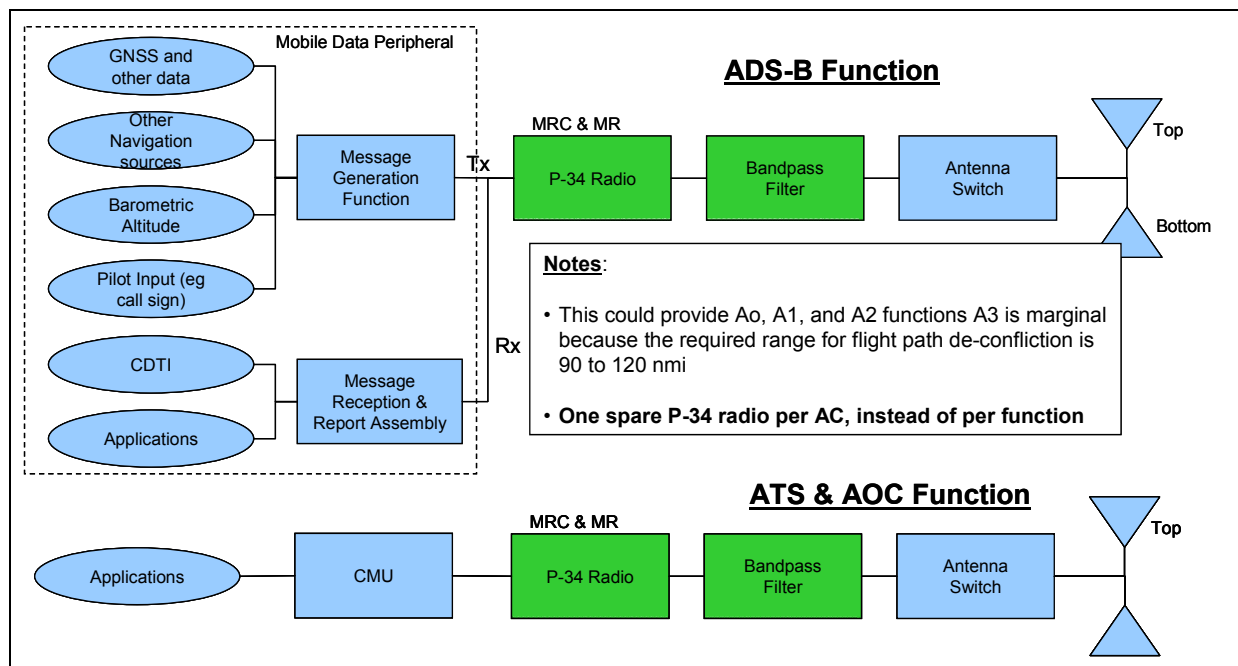


Figure 3.4-14: Avionics for P34

3.4.5 Evaluation Summary and Scores

Table 3.4-6 provides the scoring summary for APCO P25. The rationale for the assigned scores is provided in table 3.4-7.

Table 3.4-6: P25 Evaluation Worksheet

	Criteria	Surface	Terminal	En Route	Oceanic	Polar
Voice Needs	1					
Pilot-Controller Talk Group	1A1					
Pilot-Controller Selective Addressing	1A2					
Direct Pilot-Pilot	1A3					
Broadcast capability	1A4					
Capacity provided	1B1					
Address space	1B3					
Aircraft mobility management	1C1					
Latency	1C2					
Basic Data Needs	2					
A/G and G/A Addressed Data Transport	2A1					
Ground-to-Air Broadcast Data Transport	2A2					
Aggregate Data Rate	2B1					
Number of Users	2B2					
Uplink and Downlink Priority Levels / QoS	2C1					
Latency	2C2					
Enhanced Data	3					
ADS-B	3A1					
Pilot-Pilot Data Transport	3A2					
Aggregate Data Rate	3B1					
Technology Readiness Level	4					
Standardization Status	5					
Certiifiability	6					
Ground Infrastructure Cost	7					
Cost to Aircraft	8					
Spectrum Protection	10					
Security	11					
Transition	12					

Table 3.4-7: P25 Scoring Rationale

Element	Score	Rationale
Pilot-Controller Talk Group	Green (S, T, E) Red (O and P)	P25 provides this function natively where ground infrastructure exists (Surface, Terminal and En Route domains). The P25 standard, TSB-102A, defines this as a required Teleservice of P25. Specifically, this is specified in "5.4.2.2.2 Unaddressed Voice Call". A related function is also provided, the "Group Voice Call". The Unaddressed Voice call transfers communications to all radios in the coverage area. The Group Voice call is a pre-determined talk group.
Pilot-Controller Selective Addressing	Green (S, T, E) Red (O and P)	P25 provides this function natively where ground infrastructure exists (Surface, Terminal and En Route domains). The P25 standard, TSB-102A, defines this as a required Teleservice of P25. Specifically, this is defined in "5.4.2.2.4 Individual Voice Call"
Direct Pilot-Pilot	Green (all domains)	P25 provides this function natively in all domains. The P25 standard, TSB-102A, defines this as a required Teleservice of P25. Specifically, this is defined in "5.4.2.2.4 Individual Voice Call"
Broadcast capability	Green (S, T, E) Red (O and P)	P25 provides this function natively where ground infrastructure exists (Surface, Terminal and En Route domains). The P25 standard, TSB-102A, defines this as a required Teleservice of P25. Specifically, this is specified in "5.4.2.2.1 Broadcast Voice Call"
Capacity provided	Green (all domains)	Each current 25 kHz channel would be replaced by two 12.5 kHz channels. From TSB-102A: <i>The system shall give immediate channel utilization 2 times as spectrum efficient as current analog systems, representing a move from one 25kHz to two 12.5kHz channels.</i>
Address space	Green (all domains)	From TSB-102A: <i>The system, in conventional and trunked mode, shall allow each radio subsystem to uniquely identify at least 65,000 talk groups and at least 16,000,000 radio unit IDs.</i>
Aircraft mobility management	Green (S, T, E) Red (O and P)	Provides Intra- and Inter-System roaming services in covered areas
Latency	Green (all domains)	The P25 standard, TSB-102A, states: <i>Throughput delay is the propagation delay of audio through a system. Throughput delays shall be less than:</i> - 250 msec for direct radio-to-radio communications. - 350 msec for direct radio-to-radio communications through a single repeater station. - 500 msec for direct radio-to-radio communications within an RF subsystem.
A/G and G/A Addressed Data Transport	Green (S, T, E) Red (O and P)	From TIA/EIA-102.BAEB: Communications configuration point-to-point
Ground-to-Air Broadcast Data Transport	Green (S, T, E) Red (O and P)	From TIA/EIA-102.BAEB: The sending of IP broadcast or multicast datagrams over a corresponding unconfirmed service of the CAI is not supported at this time, although this may be defined as a standard service at some point in the future.
Aggregate Data Rate	Yellow (all domains)	From TSB-102A: <i>Data transmission over the RF link shall be allowed by the system at a minimum gross bit rate of 9600 BPS with minimal re-transmissions. The net bit rate that is available after deduction of overhead for error correction and re-transmission is 5.8 kbps.</i> Because of the concept of use (direct mode conventional system, with voice and data shared on the same channel) the system will not provide much data capacity.
Number of Users	Green (all domains)	Layer three is defined as IP. The IP address space clearly supports the necessary number of users.
Uplink and Downlink Priority Levels/QoS	Red (all domains)	P25 phase I is based on IPv4. The precedence field (element of "Service Type" in the header) is used to specify the level of priority using eight levels from 0 to 7. However, this field is specifically required to be set to zero in the P25 standards. Additionally, the concept of use (direct mode conventional system, with voice and data shared on the same channel) changes the MAC access from a reservation request/reservation grant system to a carrier sense collision avoidance system. As a consequence of these two factors, QoS can not be provided.
Latency	Red (all domains)	While the system would meet time delay requirements under light load, with no QoS provision, and voice blocking the data, meeting the end-to-end latency requirements will not be generally possible.
ADS-B	Yellow (all domains)	From TIA/EIA-102.BAEB: The sending of IP broadcast or multicast datagrams over a corresponding unconfirmed service of the CAI is not supported at this time, although this may be defined as a standard service at some point in the future.
Pilot-Pilot Data Transport	Green (all domains)	Radio-radio data is supported as a native feature.

Element	Score	Rationale
Aggregate Data Rate	Red (all domains)	From TSB-102A: Data transmission over the RF link shall be allowed by the system at a minimum gross bit rate of 9600 BPS with minimal re-transmissions. The net BIT rate that is available after deduction of overhead for error correction and re-transmission is 5.8 kbps.
Technology Readiness Level	Green	TRL 6. Systems are fielded and in use in Public Service aviation.
Standardization Status	Yellow	Mature commercial standards for P25 exist.
Certifiability	Yellow	Candidate developed for safety related services, and in accord with the evaluation criteria and associated metrics (see section 2 of this report) this technology is graded a "Yellow". ³⁶
Ground Infrastructure Cost	Green	System protocols, especially data, are simple and endemic. Reference architecture is straightforward. No special devices are required. The use of a constant envelope frequency modulated waveform (C4FM) should result in relaxed RF amplifier linearity requirements.
Cost to Aircraft	Green	Estimated cost is equal to 1.8 x ARINC 716 8.33/25 kHz DSB-AM analog receiver
Spectrum Protection	Green	Propose for the VHF band
Security	Green	P25 provides authentication and integrity and encryption, including OTAR.
Transition	Green	Provides a good transition path

Table 3.4-8 provides the scoring summary for APCO P34. The rationale for the assigned scores is provided in table 3.4-9.

Table 3.4-8: P34 Evaluation Worksheet

	Criteria	Surface	Terminal	En Route	Oceanic	Polar
Voice Needs	1					
Pilot-Controller Talk Group	1A1					
Pilot-Controller Selective Addressing	1A2					
Direct Pilot-Pilot	1A3					
Broadcast capability	1A4					
Capacity provided	1B1					
Address space	1B3					
Aircraft mobility management	1C1					
Latency	1C2					
Basic Data Needs	2					
A/G and G/A Addressed Data Transport	2A1					
Ground-to-Air Broadcast Data Transport	2A2					
Aggregate Data Rate	2B1					
Number of Users	2B2					
Uplink and Downlink Priority Levels / QoS	2C1					
Latency	2C2					
Enhanced Data	3					
ADS-B	3A1					
Pilot-Pilot Data Transport	3A2					
Aggregate Data Rate	3B1					
Technology Readiness Level	4					
Standardization Status	5					
Certifiability	6					
Ground Infrastructure Cost	7					
Cost to Aircraft	8					
Spectrum Protection	10					
Security	11					
Transition	12					

Table 3.4-9: P34 Scoring Rationale

Element	Score	Rationale
Pilot-Controller Talk Group	Green (S, T, and E) Red (O and P)	Streaming Audio is a Supplemental Service. Combined with multicast IP service, this function is possible.
Pilot-Controller Selective Addressing	Green (S, T, and E) Red (O and P)	Streaming Audio combined with unicast IP service.
Direct Pilot-Pilot	Green (all domains)	Streaming Audio combined with broadcast IP service.
Broadcast capability	Green (S, T, and E) Red (O and P)	Streaming Audio combined with unicast IP service.
Capacity provided	Green (all domains)	Multiple sectors could easily be supported on one broadband stream. Extremely high data rate, migration of voice to data, and DME band spectrum all contributed to the green rating.
Address space	Green (all domains)	No practical bound
Aircraft mobility management	Green (S, T, and E) Red (O and P)	HLR and VLR provide mobility management functions in coverage areas
Latency	Yellow (all domains)	While 250ms is likely very achievable with VoIP, yellow ranking was assigned to be conservative
A/G and G/A Addressed Data Transport	Green (S, T, and E) Red (O and P)	Native service
Ground-to-Air Broadcast Data Transport	Green (S, T, and E) Red (O and P)	Native service
Aggregate Data Rate	Green (all domains)	Data rate provided is between 288 and 864 kbps
Number of Users	Green (all domains)	Limited by IP address space
Uplink and Downlink Priority Levels/QoS	Green (all domains)	Provided at the IP layer
Latency	Green (all domains)	High data rate and QoS ensure that delay requirements are met.
ADS-B	Green (all domains)	Radio-to-radio (talk around) mode, combined with broadcast IP services provides this functionality. Class A3 will require a waiver, due to the limited range of the technology (150 km)
Pilot-Pilot Data Transport	Green (all domains)	Radio-to-radio (talk around) mode, combined with point-to-point and point-to-multipoint services provide this functionality.
Aggregate Data Rate	Green (all domains)	Data rate provided is between 288 and 864 kbps per channel assignment. Four 150 kHz channels in the DME band could satisfy all expanded data needs
Technology Readiness Level	Green	Rated at TRL 6, because of Pinellas County , FL wideband data project at 700 MHz (operational system)
Standardization Status	Yellow	EIA/TIA-902 series standards
Certifiability	Yellow	Candidate developed for safety related services, and in accord with the evaluation criteria and associated metrics (see section 2 of this report) this technology is graded a "Yellow". ³⁷
Ground Infrastructure Cost	Yellow	Any high data rate system will require extraordinary Telco costs. Other than the cost of Telco, the system is relatively simple, and given the concept of phasing it in after P25, would likely only require new radios and large Telco pipes.
Cost to Aircraft	Green	P34 is comparable to other candidates, which are rated low cost. Average cost of radios is projected as twice VHF.
Spectrum Protection	Yellow	Proposed for the DME band (960 to 1024 MHz)
Security	Green	P34 provides authentication and integrity.
Transition	Green	Transition issues involve de-commissioning DME ground equipment.

3.4.5.1 Technology benefits and issues, and evaluation summary

The public safety technologies that were reviewed would appear to have some potential for provisioning of A/G aeronautical communications. This should not be too surprising as the initial requirements for development of the P25 and P34 systems have a degree of commonality with the Future Air/Ground Communications system requirements. The services that are provided by P25 and P34 overlap the required services for Aeronautical A/G communications, and provide some interesting security features (the radio unit monitoring and silent emergency features of P25 would be very useful features in the advent of a hijacking for instance).

P25 provides a good feature set, and a modulation that is simple and robust. It uses C4FM modulation, which has constant amplitude and leads to relatively cheap transmitter power amplifier implementations. The physical layer employs Trellis coding, with either Hamming or Golay inner coding and interleaving to provide a robust physical layer. It is defined to provide 9.6 kbps on a 12.5 kHz channel, in either Trunking or conventional modes of operation.

P25 voice services would appear to be an excellent match for the future A/G communications system. When provisioned as a shared data and voice system, the P25 data rate is low. It does not meet the future aeronautical communications goal for basic data of 31.5 kbps, unless several frequencies are trunked together, and credit taken for an aggregate data rate as a consequence.

P34 seems to be an excellent choice for a scaleable³⁸ data system in the DME band. Its physical layer is somewhat advanced, employing scaleable signal constellations, OFDM modulation, advance pilot and symbol synchronization techniques, as well as pilot phasing to reduce the overall crest factor of the transmitted waveform.

3.5 Satellite and Over the Horizon Communications

This section provides details and background on the family of Satellite and Over the Horizon (OTH) communications systems that were evaluated as candidates for the Future Aeronautical Communications System. OTH systems were included in this section because of the similarity between Satellite communications coverage and OTH systems communications coverage geographic extent. Both systems can provide coverage over long-ranges, and into remote regions. These are unique capabilities of interest for the Future Aeronautical Communications System. For convenience, the phrase “Satellite and over the horizon systems” will be replaced by “Satellite systems,” unless it is necessary to explicitly differentiate the two types of systems.

As a prelude to technology evaluation, a representative sampling of Satellite systems was assembled. This discovery process was detailed in section 2.3.1, Technology Identification. This section presents an overview of the technologies that were identified. Because it proves useful for comparison purposes, a taxonomy of satellite systems is developed, and the identified systems are partitioned in accord with this taxonomy. One use of the taxonomy is to develop a trade space. Trade spaces prove useful in identifying solutions that have not been considered. A complete spanning of a trade space leads to a sense of completeness of evaluation, at least from a functional perspective.

Not all of the Satellite systems that were investigated appeared to provide real value in consideration of a technology applicable for the Future Aeronautical Communications System. As a consequence, some systems were eliminated from detailed evaluation. Those that were selected for evaluation are described in detail, in order to provide the technical basis for the technology evaluations. Technology descriptions include the communications services that are provided, key features, system functional architecture, and the air interface. This leads to a description of the concept of use of this technology for providing aeronautical A/G communications, including a notional physical architecture and applicable services. A set of common issues is developed for satellite systems, which includes latency, availability and avionics cost. As each system is described, some notion of how it addresses the common issues is provided.

Finally, the technologies are then evaluated and scored. From the scoring, some observations are offered that complement the evaluations and provide the authors insight as to the applicability of a technology to the functional, performance and institutional requirements of the Future Aeronautical Communications System.

3.5.1 Overview of the Family

Traditionally, satellite systems have provided communications services to remote areas or areas without the possibility for a ground infrastructure (e.g., oceanic and polar regions). While the advent of communications satellites is a relatively recent event, today there are hundreds of functional satellites providing communications services, including broadcast and mobile telephony.

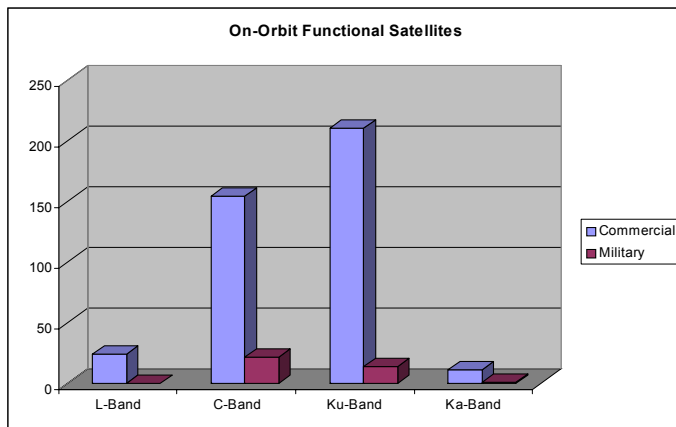


Figure 3.5-1: On Orbit Functional Satellites³⁹

Satellite communications systems may be broadly classified by their orbital characteristics, spectrum utilized, provisioning (commercial or government) and whether signal regeneration is employed. Figure 3.5-2 provides a depiction of the taxonomy that was developed to help classify satellite systems. It is called a trade space because it provides a way to partition potential solutions into groups of like things that provide approximately similar performance when used for aeronautical communications. Thus, systems that were not considered, if they are comparable to systems that were considered in the trade space, should have the same usefulness (or lack thereof) for application to meeting the needs of aeronautical air-ground communications.

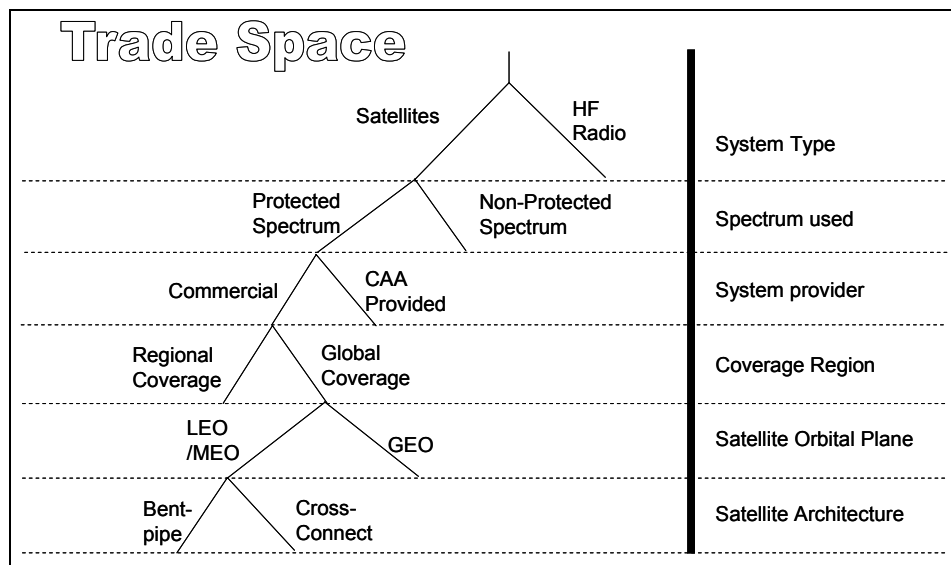


Figure 3.5-2: Taxonomy of Satellite Systems

Certain branches of the trade tree (presented in figure 3.5-2) were purposefully pruned. The HF radio branch describes a sparse set of solutions that are already defined and in use for aeronautical communications. These technologies were included for completeness, but the set is not large enough to warrant further subdivision. The branch labeled “Non-Protected Spectrum” was pruned because ICAO standards, and the ICAO Handbook on Radio Frequency Spectrum Requirements for Civil Aviation

require that aeronautical safety communications occur in mobile satellite service bands where priority is accorded to the AMS(R)S. The “CAA Provided” branch has been pruned because currently none of these systems exist. All of the branches shown under the “Commercial” branch would apply to the “CAA Provided” branch, with no functional differences. Consequentially, it was deemed appropriate to prune the tree at this branch point. The branch labeled “Regional Coverage” was also pruned. This branch is the domain of regional systems (e.g., Thuraya, MTSAT, AMSC) that go not provide global coverage, and can not meet the needs of a global interoperable system without a global common air-interface being defined for these proprietary systems, which has yet to occur. All of the other tree branches are fully developed.

Clearly, not every satellite communications system was considered for applicability to the Future Aeronautical Communications System. However, systems were identified that provide representation on every branch of the trade tree. Other systems that occupy the same branch description will likely have the same applicability to aeronautical communications, and should be considered as having been included by inference.

The satellite systems and concepts evaluated are tabulated in table 3.5-1. Clearly some systems were identified for every branch of the trade tree. In fact, several branches have more than one system identified. In general, those branches with more than one identified system were a consequence of receiving multiple responses to the NASA Request for Information (RFI) (descriptions of the NASA RFI and responses received can be found in Appendix C to this report). Most of the RFI responses were at least considered for evaluation (not all RFI responses actually provided a candidate technology), so the systems that were proposed were at least tabulated for consideration.

Table 3.5-1: Satellite Systems Considered

Satellite Architecture	Satellite Orbital Plane	Coverage Region	System Provider	Spectrum Used	System Type	Systems Considered
					HF Radio	HF Data Link
				Non-Protected Spectrum	Satellite	Connexion by Boeing Digital Audio Broadcast (XM and Sirius)
			CAA Provided	Protected Spectrum	Satellite	IGSAGS SDLS
		Regional	CAA Provided	Protected Spectrum	Satellite	Thuraya
	GEO	Global	Commercial	Protected Spectrum	Satellite	Inmarsat Boeing GCNSS Concept
Bent-pipe	LEO/MEO	Global	Commercial	Protected Spectrum	Satellite	Globalstar*
Cross-connect	LEO/MEO	Global	Commercial	Protected Spectrum	Satellite	Iridium
*Globalstar is the closest system to satisfying the trade tree constraints that exists. It actually does not use protected spectrum on both the uplink and downlink, as one of the links is at 2.2 GHz.						

For comparison purposes, table 3.5-2 provides some key parameters of the satellites systems that were considered, including the data rate provided, spectrum utilized, and whether the system would be a leased service or require Civil Aviation Authority (CAA) provided infrastructure. In the table, yellow highlighting is applied to the links that operate in the Mobile-Satellite frequency bands that require priority and preemptive service for Aeronautical Mobile-Satellite (R) Service (AMS(R)S Spectrum). The upper frequency limits of Globalstar and Iridium are highlighted because the upper portions of their allocated spectrum are in the AMS(R)S Spectrum.

Table 3.5-2: Key Parameters of Satellite Systems Considered

System	Spectrum Utilized	Data Rate Provided	Leased Service/CAA Infrastructure
HF Data Link	3 – 30 MHz ⁴⁰	300, 600, 1200, or 1800 bps depending on radio wave propagation conditions ⁴¹	Leased Service from ARINC
Connexion by Boeing	14-14.5 GHz Earth—space, (E-s) 11-12 GHz space—Earth, (s-E) ⁴²	Forward Link (E-s) up to 1 Mbit/s— Return Link (s-E) up to 5 Mbit/s ⁴³	Leased Service from Boeing (and indirectly from Satellite service providers)
Digital Audio Broadcast (XM and Sirius)	2.320 to 2.345 GHz ⁴⁴	Proprietary. Approximately 100 channels, each providing 48 kbps.	Leased Service
IGSAGS	960 to 984 MHz (S-e) 1008 to 1032 MHz (e-S) ⁴⁵	30 Kbps ⁴⁶	CAA Infrastructure
SDLS	<u>Mobile Links</u> E-s 1646.5 to 1656.5 MHz s-E 1545.0 to 1555.0 MHz <u>Feeder Links</u> E-s 6.4 or 14 GHz s-E 3.6 or 12 GHz ⁴⁷	From 6.4 kbps in global beam to 30 kbps in spot beams. ⁴⁸	CAA Infrastructure
Thuraya	<u>Mobile Links</u> E-s 1626.5 to 1660.5 MHz s-E 1525.0 to 1559.0 MHz <u>Feeder Links</u> E-s 6425.0 to 6725.0 MHz s-E 3400.0 to 3625.0 MHz ⁴⁹	Fax/Data at 9.6kbps ⁵⁰	Leased Service
Inmarsat (includes Boeing GCNSS Concept)	<u>Mobile Links</u> E-s 1626.5 to 1660.5 MHz s-E 1525.0 to 1559.0 MHz ⁵¹	432 kbps per channel ⁵²	Leased Service
Globalstar*	<u>Mobile Links</u> E-s 1610 to 1626.5 MHz s-E 2483.5 to 2500 MHz <u>Feeder Links</u> E-s 5091 to 5250 MHz s-E 6875 to 7055 MHz ⁵³	Up to 9.6 kbps ⁵⁴	Leased Service
Iridium	1616 to 1626.5 MHz ⁵⁵	2.4 kbps ⁵⁶	Leased Service

3.5.1.1 Synopsis of Considered Systems

A brief overview of each of the satellite systems considered is provided below.

Inmarsat Family—The Inmarsat family consists of four constellations of satellites, the fourth of which are expected to be launched in late 2004 and early 2005. Inmarsat came into being as an intergovernmental organization in 1979 to provide global safety services as well as other communications services for the maritime community. Inmarsat constellations two and three have been providing aeronautical services since the early 1990s. In 1999, Inmarsat became the first intergovernmental organization to be transformed into a private company. Inmarsat services include “Classic” Inmarsat Aeronautical Mobile Satellite Services, Swift 64, and Swift Broadband (Aero-BGAN or Inmarsat IV).

Thuraya—Thuraya is a regional mobile satellite system that provides telephone services. Thuraya was established in April of 1997 as a private joint stock company in the United Arab Emirates (UAE). There are currently two Thuraya satellites in orbit and a third satellite is being developed to expand system capacity.

Boeing CNS Satellite Concept—Boeing offered a response to the NASA RFI, which was essentially a synopsis of their work on the Global Communication, Navigation, and Surveillance System (GCNSS) Program. The Boeing proposal calls for transitional use of existing satellites before an eventual system would be provisioned by the FAA. Initial cost benefits require use of the Inmarsat constellation in the time frame of this study.

Sensis proposed Integrated Terrestrial and Satellite Hybrid System—Sensis proposed an Integrated Terrestrial and Satellite Hybrid system in a response to the NASA RFI. The information in the RFI is proprietary, but in general terms, both a ground segment and a satellite segment were specified. The satellite segment could be used for broadcast and addressed data delivery. Example technologies were provided, and the concept is sound. While the proprietary nature of the response prohibits its discussion in this document, the system concept overlaps other technologies that *are* discussed in this document.

SDLS—Satellite Data Link System (SDLS) is a European Space Agency (ESA) funded development effort to provide improved communications services through a satellite based system specifically oriented towards the safety related services. The development has been led by a European industrial consortium led by Alcatel Space Industries and including Thales, Indra and Airtel. The SDLS system would use existing or future bent-pipe geostationary satellites and CDMA at L-band. The design goals of SDLS are low cost infrastructure and low operational costs. An initial feasibility study has been completed and a demonstrator baseline system qualified in July 2002. An operational system study is on-going.

IGSAGS—Integrated Global Surveillance and Guidance System (IGSAGS) was proposed in a response to the NASA RFI. The proposed system is a custom satellite solution, where the satellites would be provisioned by the FAA (or other Civil Aviation Authorities). IGSAGS would require an investment in a large number of satellites, with approximately 16 being specified in the system concept. Both polar orbits and geostationary orbits would be required. Voice and data would be provided by dividing the DME band into narrow band channels, with each channel each providing digitized voice and low rate data. Satellite-to-air and air-to-satellite transmissions would be full duplex. An optional ground segment is defined, and simplex ground-air channels are specified in the frequency guard band necessitated by the duplex operation of the satellite. A consequence of the low system data rate is that aircraft could use omnidirectional antennas, which should substantially reduce avionics costs.

Connexion By Boeing—Connexion by Boeing (CBB) is a high data rate system targeted at APC and AAC communications. Boeing indicates that extension to ATS and AOC communications seems feasible given the time frame of the study. CBB uses leased transponders in the Ku-band (un-protected spectrum) on geostationary satellites to provide Internet connectivity to aircraft in flight.

Globalstar—Globalstar consists of 48 satellites with altitudes of 1414 km. Each satellite has 16 beams and uses thirteen 1.25 MHz CDMA sub-bands. An elongated beam pattern minimizes handovers between beams. The satellites provide coverage to roughly 80% of the Earth's surface, with coverage limited by the requirement that the GES and the originating AES must be in the same satellite footprint. Globalstar satellites use bent-pipe transponders that route all traffic directly between the mobile terminals and ground earth stations (GES). GES act independently from each other, giving GES operators full control over call routing.

Iridium (including Iridium Netted Radios)—Iridium consists of 66 satellites (plus 13 orbiting spares) in low Earth orbit. Subscribers communicate to an Iridium satellite main mission antenna at 1616 to 1626.5 MHz. Iridium provides voice and low bandwidth data services. The Iridium constellation is the only system that provides truly global coverage.

HF Data Link—HFDL is a certified data link used to transfer messages between HF (3 to 30 MHz) ground stations and avionics systems on aircraft. ARINC is the sole provider of HFDL service through their GLOBALink/HF Data Link service. HFDL is used to provide AOC data link communications and uses the same Air-Ground and Ground-Ground messaging protocols as VHF and SATCOM systems. Air-Ground Message Transmission Speed varies depending on radio wave propagation conditions between 300, 600, 1200, and 1800 bps. The HFDL has ICAO SARPS and a HFDL Technical Manual, RTCA MASPS and MOPS, and AEEC Specifications. HFDL service at present is provided through 14 ground stations which are located worldwide, and traffic transferred through the service currently exceeds 400,000 messages per month. The HFDL service is relatively new, and site and system upgrades are continuing. Coverage is being improved through the addition of ground stations and HF frequencies, and ATC validation efforts are ongoing.

3.5.2 Selection of Evaluation Candidates via Minimum Threshold Test

Not all satellite systems were fully evaluated. Some were eliminated from further consideration because of the following constraints:

- **Unprotected Spectrum.** ICAO standards, and the ICAO Handbook on Radio Frequency Spectrum Requirements for Civil Aviation require that aeronautical safety communications occur in mobile satellite service bands where priority is accorded to the AMS(R)S. Systems that operate in unprotected spectrum are susceptible to interference and/or jamming, which could potentially diminish the integrity of safety of life services.
- **Technical Maturity.** Some systems are not in an advanced stage of standardization, while other systems are not even in any stage of standardization. It is unreasonable to assume that proposed concepts with currently undefined requirements will reach a sufficient level of maturity for deployment in the 2015 time frame. In general, systems that have not advanced through proof of concept (TRL 3) were discarded.
- **Regional Coverage.** Systems that only provide coverage to a region of the globe that does not include the entirety of continental United States, Europe, and the oceanic Flight Information Regions under FAA control were discarded.

Table 3.5-3 lists all of the Satellite candidates and gives a rationale for filtering out some and bringing others forward for formal evaluation. The three candidate solutions we have selected to evaluate further are identified in green.

Table 3.5-3: Application of Minimum Threshold Criteria to Satellite Systems

System	Evaluate	Rationale
HF Radio		
HF Data Link	No ⁵⁷	This is a currently operational system that provides low rate data to remote regions. It is clearly not the future system, as it provides no mechanism to relieve spectrum congestion in the VHF Band, a primary driver for the specification of the Future Aeronautical Communications System. The HF Data Link will have a role in providing aeronautical communications for some time, and roadmaps showing the implementation of the future system should show the HF Data Link as a component of the current system.
Systems Operating in Non-protected Spectrum		
Connexion by Boeing	No	This system operates as a secondary user in a non-AMS(R)S band. Had it been evaluated, it would have merited a score similar to AeroBGAN. While CBB offers a higher data rate than Aero-BGAN, Aero-BGAN operates in an AMS(R)S band that provides priority and pre-emption to aeronautical services. Since the rate provided by BGAN was deemed sufficient to provide the services that can be provided by satellite systems, the difference between the two systems does not impact their score.
CAA Provided Systems		
IGSAGS	No	The described system is conceptual, and has not reached a sufficient level of maturity to believe that it could be implemented in the study time frame.
SDLS	Yes	This system has been designed and specified to provide ATS and AOC A/G communications. The difference between this system and the IGSAGS is that a fairly significant amount of system engineering has been conducted developing the requirements for SDLS, specifying the air interface, and developing a prototype system for demonstration purposes. It is at a much higher level of maturity as a consequence, and was evaluated as a representative member of this branch of the trade tree.
Regional Coverage Systems		
Thuraya	No	System provides regional coverage only (parts of Europe, Africa, and Asia). The air interface does not share commonality with other regional systems, and as such it can not meet the needs of a global interoperable system.
GEO Systems		
Inmarsat	Yes	This system has historically been used for aviation, and has robust and interesting features.
Boeing	No	Ultimate recommendation of GCNSS study was to use Inmarsat satellites. Inmarsat is already being evaluated.
Sensis	No	The described system is conceptual. It utilizes a hybrid physical layer that can be provided by emerging standards and commercial satellites for information broadcast.
LEO/MEO Systems		
Iridium	Yes	Only system that provides truly global coverage. General Aviation avionics exist and are in use.
Globalstar	No	Does not operate in protected spectrum. Does not provide oceanic coverage.

3.5.3 Technology Descriptions

Brief descriptions of Inmarsat, SDLS, and Iridium are provided in the following sub-sections. This description provides a basis for the technology evaluations. Details are provided on services provided, the technology functional architecture, and the technology air interface.

3.5.3.1 Inmarsat

Aeronautical Mobile Satellite Services (AMSS) utilizing the INMARSAT-3 satellites have been available since the early 1990s. The AMSS Data-2, “Classic” service is the only satellite service currently approved for use for Air Traffic Services (ATS). This service has been key to the ability to use datalink in support of the Future Air Navigation System (FANS)-1/A. Approximately 2000 air transport aircraft are equipped to use the AMSS Data-2 service.

Since the INMARSAT 2 and INMARSAT 3 satellites will most likely be past the end of their useful life in the study time frame, the discussion provided below will center on the INMARSAT 4 constellation of satellites, and the services that they will provide. This system was initially described in the literature as Aero-BGAN, although INMARSAT has recently decided to call the service Swift Broadband, to harmonize the service name with the Swift64 service that was introduced in 2002.

3.5.3.1.1 Inmarsat Functional Architecture

The Inmarsat system architecture is presented in figure 3.5-3. The system will consist of two I4 satellites in orbit, with a third that will either be launched to provide Pacific Ocean coverage, or kept as a ground spare. To deliver its services, Inmarsat calls and data connections are linked into a data core network (DCN) through a pair of Satellite Access Station (SAS), one in Fucino, Italy, and the other in Holland. Data is distributed via the DCN to points-of-presence which provide connectivity to the telephone network, packet networks, and ISDN. A network operations center (NOC, which monitors and manages network traffic), satellite control center (SCC, which monitors the satellites and performs telemetry tracking and control functions) and billing operations center (BOC, which handles customer billing and fault management) complete the architecture.

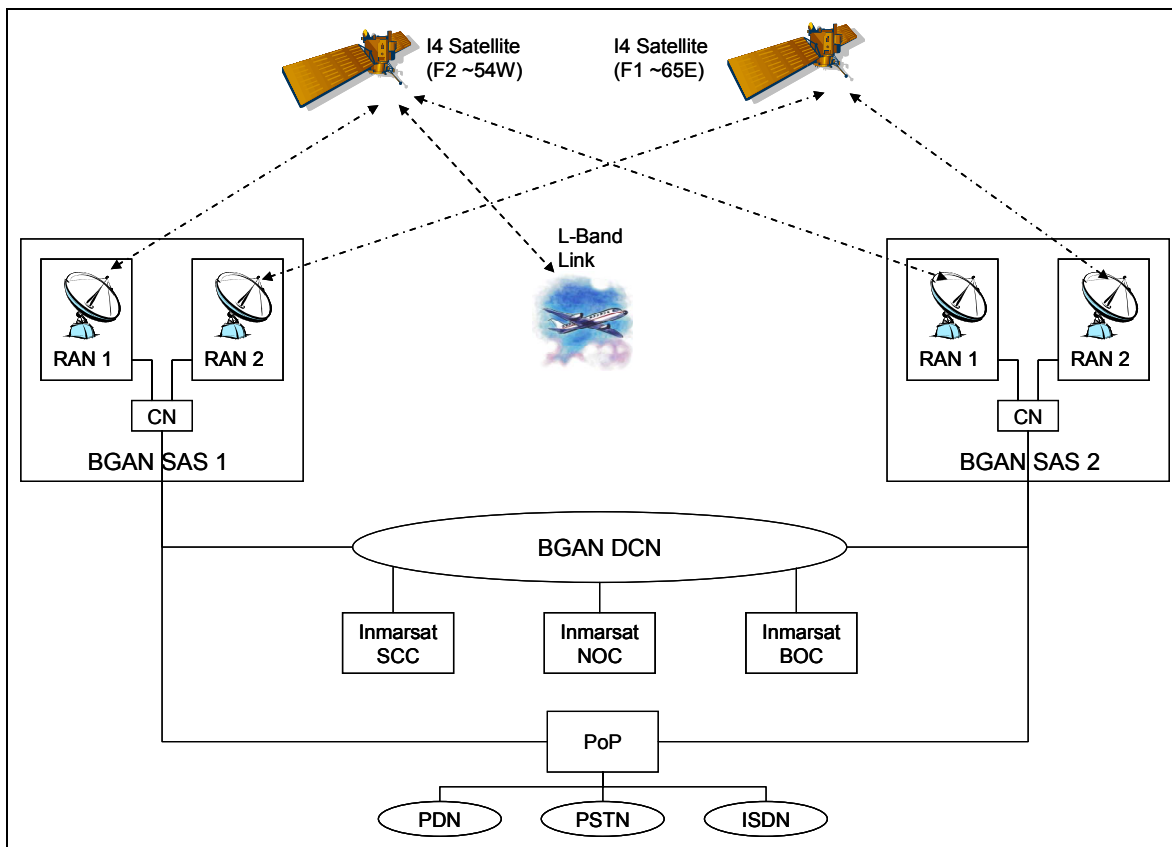


Figure 3.5-3: Inmarsat System Architecture

3.5.3.1.2 Inmarsat Air Interface Description

The INMARSAT 4 satellites will have spot-beam coverage over the continental United States that will likely result in approximately 7 to 8 spot beams over the US. In each spot beam up to 16 200 kHz TDMA channels will be provided. Frequency channelization of the available spectrum results in a seven beam frequency reuse pattern, akin to terrestrial cellular networks. The consequence is that the INMARSAT 4 satellite will be able to supply about 60 channels to the continental United States airspace⁵⁸. Figure 3.5-4 shows the projected coverage of the INMARSAT-4 53W satellite spot beams.

INMARSAT user links are in L-Band spectrum, using the frequencies between 1525 and 1559 MHz for receive (satellite to mobile user) and 1626.5 to 1660.5 MHz to transmit (mobile user to satellite). INMARSAT channels have a bandwidth of 200 kHz. Modulation can be either QPSK or 16-QAM, and would appear to be adaptive.

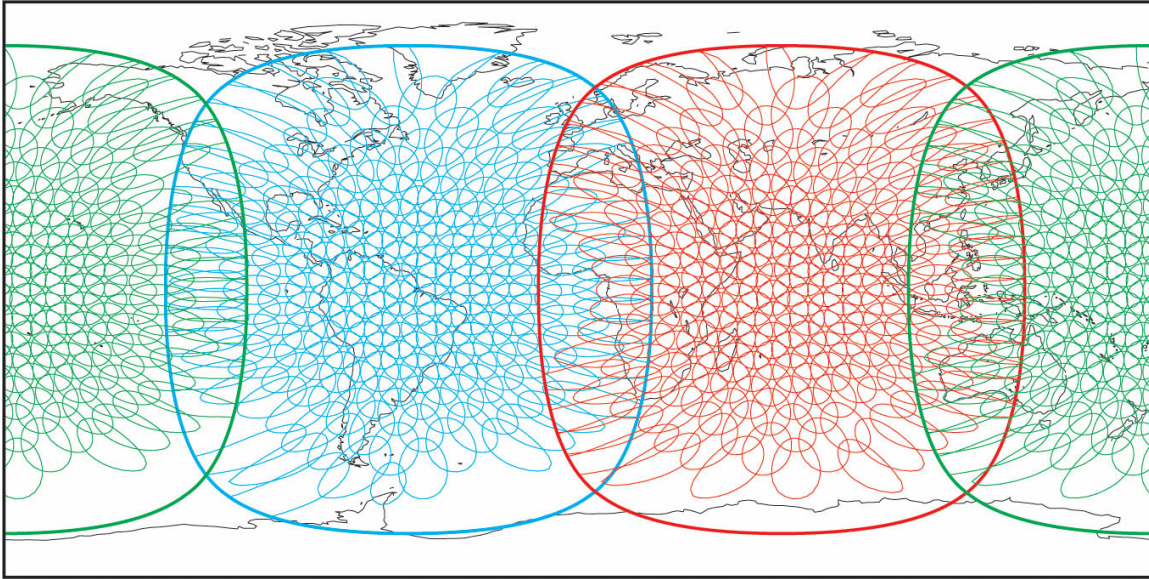


Figure 3.5-4: Spot Beam Coverage of the Inmarsat-4 Satellites⁵⁹

3.5.3.1.3 *Inmarsat Services Provided and Key Features*

Inmarsat offers three suites of services: Classic Inmarsat Services, Swift64, and BGAN.

Classic Inmarsat. Classic services include a packet mode and a circuit mode providing satellite voice communications. Data rates available for AMSS packet mode depend on the aircraft antenna gain and vary between 600 to 10,500 bps. The AMSS Data-2 service is approved for use for ATC. ICAO adopted a standard for AMSS in 1994 and has supported FANS-1/A. ICAO ATN communications will use the AMSS Data-3 packet mode service, which is already implemented in the satellite network. Approximately 2000 air transport aircraft are equipped to send ACARS data link using AMSS Data-2 packet mode service. The classic AMSS services are supported by the Inmarsat I-3 constellation and will continue to be supported by the new I-4 constellation.

Swift64. Swift64 is an aeronautical derivative of land mobile service and is provided through separate ground stations from the classic AMSS service. ISDN service (circuit mode) was introduced in 2002, while Mobile Packet Data Service (MPDS) (packet mode) became available in 2003. Swift64 services provide a nominal data rate of 64 kbps, but the effective data rate can be increased through compression and channel bonding.

BGAN. Inmarsat plans to offer Broadband Global Area Network (BGAN) services over its Inmarsat I-4 constellation. A suite of services dedicated to aeronautical customers, Aero-BGAN, will become available in 2006. BGAN will offer a nominal data rate of 432 kbps and will support Quality of service (QoS). Both packet and circuit services will be offered. BGAN services are inherently IP-based. Connections to PSTN, ISDN and IP networks will be supported, as was shown in the BGAN functional diagram presented in figure 3.5-3.

BGAN Packet Services will include the following:

- DSL class Internet Access
- Static and Dynamic IP Addressing
- Bandwidth on Demand
- Basic IP Services
 - UMTS “Background/Interactive class”
 - Variable Data rate

- Premium IP Services
 - Streaming
 - Guaranteed Bit Rate

BGAN Circuit Services include the following:

- Direct Dial Voice
- SIM Roaming
- Voice Mail Services
- Other UMTS Services
- CLI, Call divert, conference calling etc.
- SMS (Two way)
- ISDN

3.5.3.2 SDLS

The SDLS concept calls for the use of existing or future Geostationary satellites to provide both regional (using spot beams) and global coverage for the provisioning of aeronautical air-ground communications. The system concept supports both ATC and AOC communications. By implementing a number of complementary regional systems (each providing coverage over a wide area) a global interoperable system could be defined. A fundamental goal of the system development is to develop cheap aviation and ground infrastructure.

3.5.3.2.1 SDLS Functional Architecture

The SDLS system functional architecture is shown in figure 3.5-5. The system requires a space segment, ground segment, support segment and user segment.

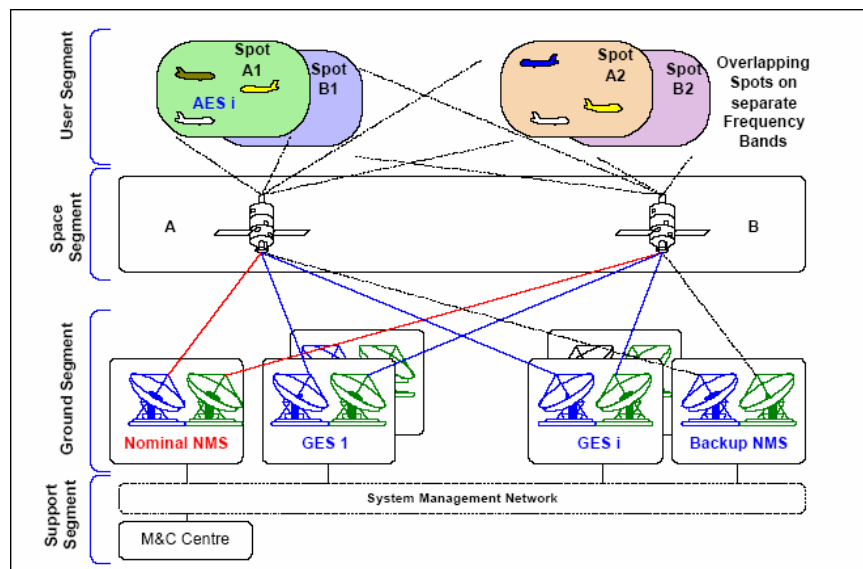


Figure 3.5-5: SDLS Functional Architecture⁶⁰

The SDLS space segment includes geostationary satellites (the concept documents say two, but Boeing availability analysis indicates we would require three Geostationary satellites providing overlapping coverage to achieve 99.9987% availability) that can provide a transparent transponder between the feeder link (ground station to satellite) and the mobile link (satellite to AES). Spot beams are required, as well as channels in the AMS(R)S band.

The SDLS ground segment requires the provisioning of a Network Master Stations (NMS), Ground Earth Stations (GES), and network routing equipment. The support segment requires system management network connectivity to the ground segment components and a monitoring and control facility. While it isn't explicitly stated in any of the SDLS documentation, it seems likely that the Ground Segment and Support Segment of SDLS would be provisioned by the CAA. The user segment consists of AES equipment, which is specified to include a passive low gain antenna, air cooled high power amplifier, SDLS transceiver, and a LAN with (presumably) an ATN router. It is expected that the GES would use Very Small Aperture Terminal (VSAT) technology.

3.5.3.2.2 *SDLS Air Interface Description*

Aircraft earth stations (AES) communicate to an SDLS satellite using L band frequencies (Satellite to AES 1545 to 1555 MHz, AES to Satellite 1646.5 to 1656.5 MHz). Communications between SDLS and ground stations operate in either the C or Ku bands.

To support different user communications, SDLS uses Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA). The CDMA is accomplished using gold-codes with a spreading factor of 127. The TDMA structure depends on the particular channel (multiple channels are defined, and some discussion of the various channels is provided below). The basic modulation is QPSK, and rate $\frac{1}{2}$ Turbo-coding is specified.

The SDLS specification defines a number of carriers and channels. Using the nomenclature provided in the SDLS Demonstrator documentation, the carriers include a Forward Reference Carrier (FRC), Return Reference Carrier (RRC), Forward Common Carrier (FCC), Forward Auxiliary Carrier (FAC), Return Common Carrier (RCC), Return Auxiliary Carrier (RAC). These definitions stem from European Space Agency's applications (MSBN in particular) developed for the EMS (European Mobile Services) payload operational on the telecommunications satellite Italsat F2. ESA retains a limited part of the EMS capacity to continue experimentation with MSBN. MSBN is a real-time voice and data communication system with the emphasis on decentralized, low-capacity applications.

The physical carriers provide for a number of logical channels. The Forward Traffic Carrier provides the forward traffic channel for general purpose data (Pd) and the forward traffic channel carrying system management information (Psmc). Voice Channels (C) are provided on the Forward Traffic Carrier and the Return Traffic Carrier (more specifically, the Return Raw CDMA Traffic Carrier, RRTC). A complete mapping of channels to carriers, and the specifics of the carrier modulation and framing is provided in the SDLS Slice 3 Executive Summary, Table 4⁶¹.

3.5.3.2.3 *SDLS Services Provided and Key Features*

SDLS provides both Teleservices and bearer services. The Teleservices are ATN SARPS compliant services for ATS and AOC and include such things as Data Link Initiation Capability (DLIC), Controller Pilot Data Link Communications (CPDLC), and Flight Plan Consistency (FLIPCY). AOC services include weather information, aircraft movement control, flight planning, fuel information, aircraft maintenance and airport/airway operational information (NOTAMS). The bearer services provided by SDLS include connected data service, point-to-point voice service, datagram service, automatic position reporting service, party line service (broadcast) and party line service (demand). Figure 3.5-6 shows the services provided by SDLS. There is a provision for a short data service (indicated by the text box "Provisions" in fig. 3.5-6). In the figure, the labels on the services, "Data 1," "Data 2," etc., are not intended to indicate the relative priorities of these services, but are just name tags, used to differentiate between the various services being provisioned.

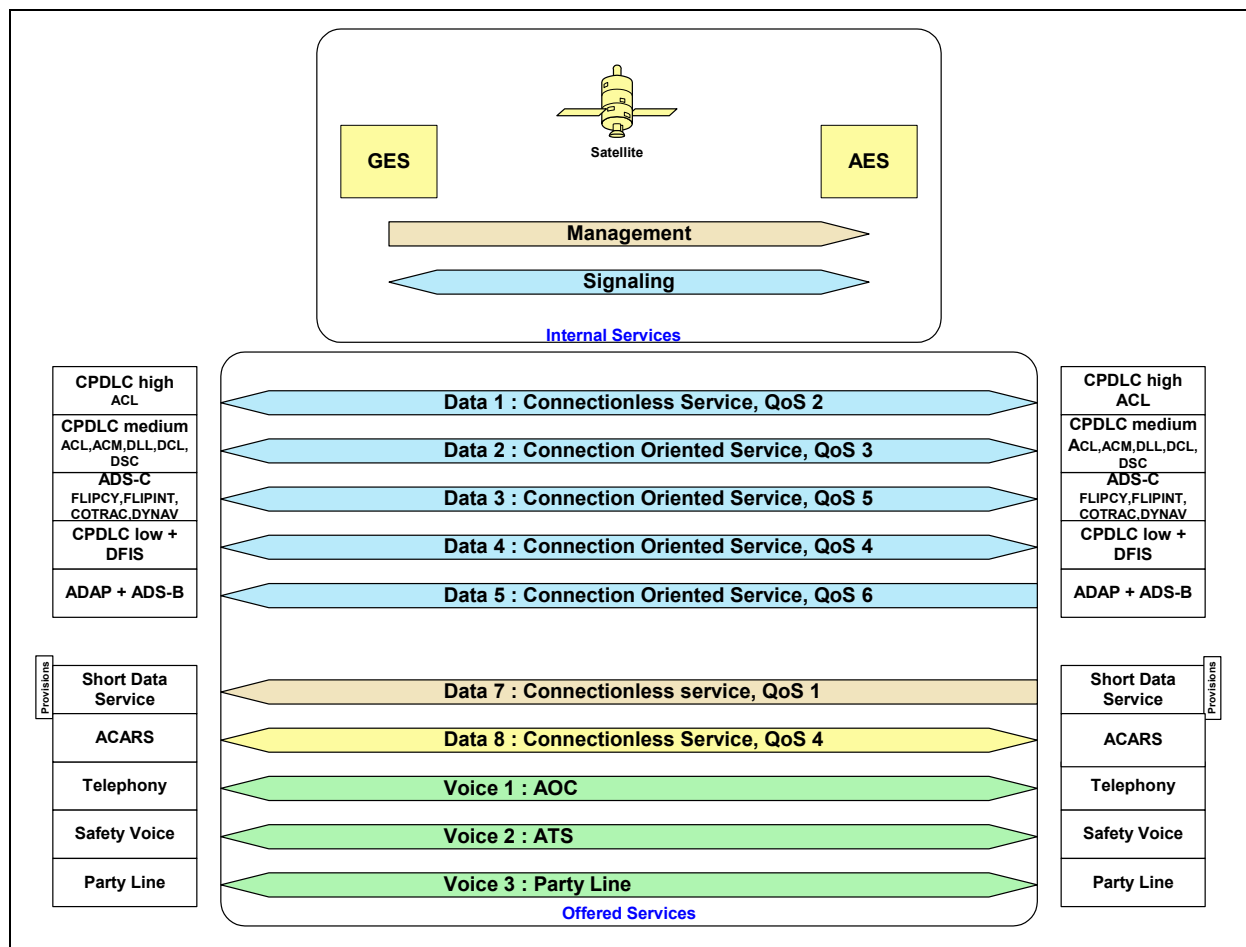


Figure 3.5-6: SDLS Services⁶²

The SDLS voice services include party line and point-to-point exchanges. Prioritization of voice communications (controller override) is supported, as is talker ID. The services are being developed to provide fast call setup. The party line service would provide a constantly on service to the controller.

SDLS defines Quality of Service (QoS) parameters for 6 data and 3 voice services classes. The data services classes define transit delay, residual error rate, priority, and data flow directions in their QoS definitions. Each data service QoS can be mapped to ATS or AOC applications, for instance, the QoS 2 Service could transport high priority CPDLC messages.

The SDLS Voice service classes include ATC and AOC classes. The ATC class is further divided into point-to-point and point-to-multipoint (for party-line) classes. The Party-line service class is defined to have a permanent connection, providing a service that is equivalent to today's VHF voice communications. Complete descriptions of the SDLS QoS classes are provided in the SDLS Executive Summary⁶³, Tables 2 and 3. The bearer services are specified in the SDLS Demonstrator Final Report⁶⁴, Table 3.

3.5.3.3 Iridium

The Iridium constellation is comprised of 66 satellites (plus spares) in low earth orbit (LEO) of about 780 km altitude in 6 planes. Satellites are evenly spaced within each orbital plane and offset by half-satellite spacing from satellites in adjacent orbital planes. With the exception of satellites in orbital planes

1 and 6 satellites rotate in the same direction. There is at least one spare satellite in each orbital plane. Orbits are stationary with respect to the earth's axis and the earth rotates beneath them.

Each satellite uses phased array technology to form a tightly packed group of 48 beams which together form a footprint with a diameter of about 4500km at the equator (see fig. 3.5-7). Within the footprint beams near the center are somewhat smaller than those on the edge. The average size of a beam is 560 km diameter. Towards the poles, satellites converge and their beams increasingly overlap. To ensure an even loading of converging satellites the outer beams are selectively switched off. Above about 60 degrees North there is total overlap.

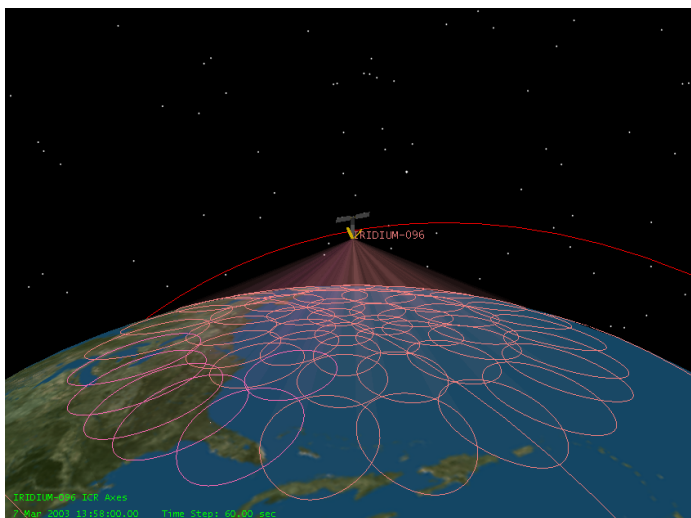


Figure 3.5-7: Iridium Space Vehicle Spot Beam Footprint

3.5.3.3.1 *Iridium Constellation Viability*

The costs of launching this system and developing the associated ground infrastructure were quite high, totaling nearly six billion dollars. While the original company that launched and developed the Iridium system has declared bankruptcy, the current owner of the constellation, Iridium Satellite LLC, has had a positive cash flow since 2003, with fixed operations costs.⁶⁵ The corporate marketing philosophy is to target vertical market slices, including aviation.⁶⁶

A satellite reliability and constellation lifetime assessment was performed in 2001 by the Aerospace Corporation at the behest of Iridium Satellite LLC. This assessment projected the satellite constellation global availability through mid-2010. A second reliability and constellation lifetime assessment was performed by Boeing, using a more sophisticated model of the space vehicle battery structure (the identified limiting factor in the Iridium space vehicle life). This study predicts global service availability (at least 66 satellites still on orbit) through late 2014.⁶⁷

With this data as its planning baseline, Iridium Satellite LLC has developed a plan to replenish the satellite constellation. Current plans are to begin specifying system requirements and supplier selection in 2008, conduct a Preliminary Design Review in 2010, and launch of the first two satellites in the fourth quarter of 2013. Launches would occur at the rate of two per year thereafter, corresponding to the predicted failure rates of the current constellation. Predicted spares average six on orbit spares through 2020, with never less than five on orbit spares.⁶⁸ The plan seems sound from both a financial and engineering perspective, and portends an Iridium constellation that is healthy and viable through the year 2020.

3.5.3.3.2 *Iridium Functional Architecture*

The Iridium functional elements include Aircraft Earth Stations (AES), satellites, and gateways. These elements interact as shown in figure 3.5-8. Basic system operation can be described as follows. The AES initiates a call to the nearest satellite, and the satellite authenticates the AES through the gateway. If the destination is part of the public switched telephone network (PSTN), the call is routed from the originating satellite to the gateway, which in turn connects the call through the PSTN. If the destination phone is another AES, the call is routed from originating satellite to neighboring satellites and so on until it reaches the satellite that can transmit directly down to the destination AES.

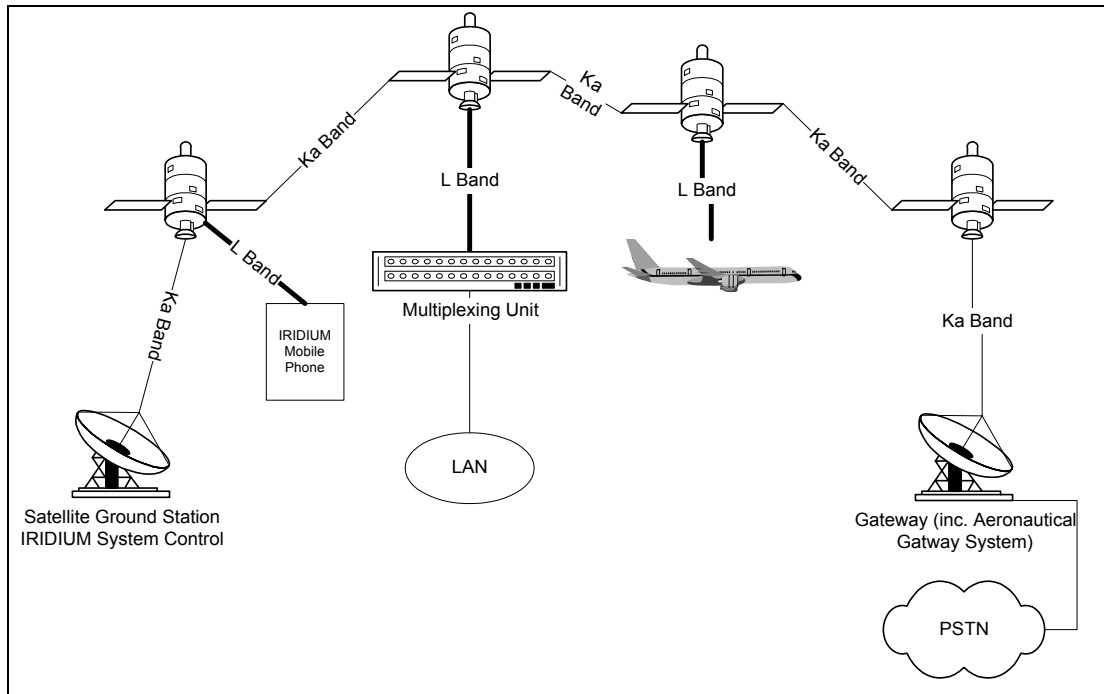


Figure 3.5-8: Iridium System Model and Physical Architecture

3.5.3.3.3 *Iridium Air Interface Description*

Aircraft earth stations (AES) communicate to an Iridium satellite main mission antenna using L band frequencies (1616 to 1626.5 MHz). Communications between Iridium satellites utilize cross-link antennas at 23.18 to 23.38 GHz while communications between Iridium and ground stations operate in the Ka-band (19.4 to 19.6 GHz and 29.1 to 29.3 GHz).

To support different user communications, Iridium uses a hybrid of Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA). The Iridium FDMA access scheme is implemented by dividing the available L-band frequencies⁶⁹ into 240 frequency channels for duplex operations and 12 frequencies for simplex operations. The available channels must be shared across all of the spot beams, which requires a frequency reuse pattern to allocate some fraction of the 240 channels to each spot beam. The best available information indicates that Iridium uses a frequency reuse pattern of 12, meaning that there are nominally (nominally, because some breathing—shifting of frequencies to accommodate peak demands—between cells is potentially accommodated) 20 frequencies available in each spot beam.

On each FDMA channel, a TDMA scheme is implemented by defining 4 uplink and 4 downlink time slots. Each time-slot pair defines a user channel and provides up to 2400 bps data rate to an individual end user.

Each end-to-end connection between users may use different types of Iridium channels (system overhead channels and bearer service channels) during the course of a communication. A sample sequence of events is as shown in figure 3.5-9.

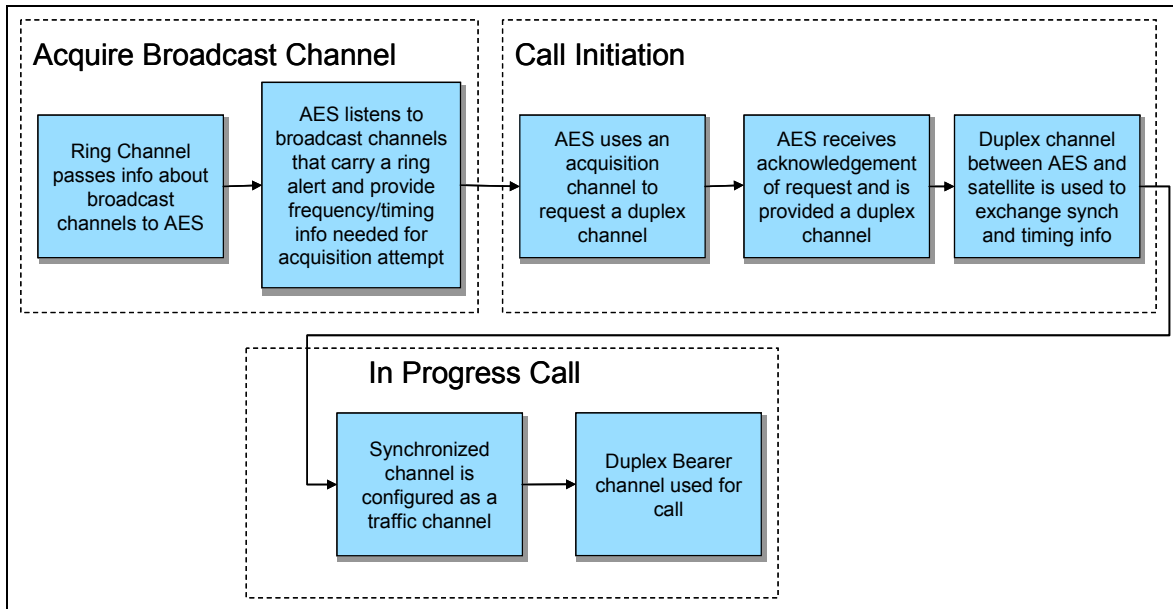


Figure 3.5-9: Iridium Call Setup Process

A summary of published (by ICAO AMCP WG-A) quality of service values for the Iridium Aeronautical Safety Service is shown in table 3.5-4.

Table 3.5-4: Iridium QoS Values

Parameter	Published Value
System Availability	0.995 across entire air/ground Iridium network; 0.9999 per hour
Continuity of Service	0.99999 per 10 mins
Latency (transfer delay assuming no competing traffic)	270 to 390 ms (5.2 and 1.64 ms are min and max 2-way propagation delays)
95% Transfer Delay for Packet Data (128 octets)	2 sec
Mean Circuit Setup Delay	20 sec
Residual Packet Error Rate (128 octets)	Better than 10^{-6}

3.5.3.3.4 Iridium Services Provided and Key Features

Iridium provides both data and voice services. Data services are primarily circuit switched, but Iridium has developed applications that provide packet switched data. Short burst data messages and a proprietary protocol (RUDICS, for Routed Unstructured Digital Interworking Connectivity Service) provide packet switched data. In addition, Short Message Service (SMS) is supported. Iridium clearly used GSM as a model for their air interface development, and SMS is a GSM defined capability that provides mobile to mobile text messaging functionality.

3.5.4 Concept of Use: Application to Aeronautical A/G Communications

In this section, the application of Inmarsat, SDLS and Iridium to aeronautical A/G communications will be discussed. As a prelude to that discussion, a short foray into some general issues associated with the use of satellite communications for the Future Aeronautical Communications System will be conducted.

3.5.4.1 General Issues Associated with use of Satellite Communications for the Future Aeronautical Communications System

There are several issues associated with use of satellite communications, in general, for aeronautical communications. These issues include, but are not limited to:

- **Availability.** All air-ground communications for ATS are *critical* services as defined in the NAS SR-1000. Critical services have constraints imposed on availability (0.99999), elimination of single-points of failure, restoral time (goal of six seconds) and outage frequency (no more than once a week).⁷⁰ Eliminating single points of failure would indicate coverage from at least two satellites. The availability constraint of five-nines might require an additional satellite. Needless to say, the restoral time of six seconds is *very* challenging for a satellite communications infrastructure.
- **Avionics.** Traditional SATCOM avionics are expensive, heavy, voluminous power consumers that generate lots of heat, introduce additional drag on the aircraft (reducing fuel efficiency), and require significant downtime to install. Cost of these avionics is a key constraint that has limited the adoption and deployment of satellite communications for aeronautical purposes.
- **Latency.** One-way latency can be an issue for satellite communications. Geostationary satellites orbit at altitudes approximately 36,000 kilometers. At this range, propagation delay from a GES to the satellite and then down to the Airborne Earth Station (AES) is roughly 240 ms.
- **Call Setup times.** Setting up a voice call can be a time consuming process, and depends on both the transit latency and call initiation protocol. Most protocols require several round trip messages in order to set up a voice call. For example, SIP requires a minimum of two round trip messages. When the one-way latency between end points in the call setup process is long, call setup times can be on the order of seconds.

3.5.4.1.1 *Availability Considerations for A/G Communications via Satellite*

In considering satellite availability, several issues need to be addressed. Very detailed descriptions of each of these elements may be found in Appendix C of RTCA/DO-270, Minimum Aviation System Performance Standards (MASPS) for the Aeronautical Mobile-Satellite (R) Service (AMS(R)S) as Used in Aeronautical Data Links.

- **Feeder link rain fade.** Most feeder links operate in spectrum that can be severely attenuated by rain, and deep fades can interrupt communications from the satellite access point to the satellite. The mitigation of this (loss of communications continuity) requires the use of two satellite access points, with enough physical separation (on the ground) that the incidence of rain fades on the feeder links will be uncorrelated. (This is a consideration for architectures where the uplink communications is on the satellite feeder links. If systems are proposed that use only the L-Band spectrum for both uplink and downlink communications, then this particular item does not apply. It should be noted that the normal expectation is that fixed ground infrastructure communications to mobile terminals is via the feeder link.)
- **Ionospheric Scintillation.** The user data link (required to be in L-Band) can experience Ionospheric scintillation induced disruptions due to short-term Ionospheric induced signal fading. Measurements at 1.5 GHz show fades greater than 20 dB,⁷¹ which would generally mean loss of lock for most satellite communications systems. To mitigate this effect, uncorrelated paths between the user (aircraft) and the satellite are required. This in essence means two satellites, with very different look angles, will be required.
- **System Component Failures.** While all of the system components (Satellites, Ground Earth Stations, Network Control Stations and Aircraft Earth Stations) must be included in and availability analysis, the dominant contributor to system cost is the number of satellites that will be required to meet the stated availability requirements of a system. For a host of reasons, satellites fail. Both on-orbit sparing, and ground-based sparing techniques are employed by the industry to limit system outage times (Iridium used on-orbit sparing, and INMARSAT is planning ground-based sparing for their I-4 constellation). Each of the techniques has a ramification on overall system availability calculations, but in general, the combination of Ionospheric

Scintillations and catastrophic satellite failures works to push the number of functional satellites per coverage region to three.

- **Aircraft Maneuvering.** Satellite to mobile links are line-of-sight links with (typically) small link margins. Shading by the aircraft fuselage, or wing during maneuvers can disrupt air-ground communications in most satellite communications systems.

Boeing has studied this problem extensively. The work that they present in their System Architecture Description Document provides analysis of several satellite constellations.⁷² The conclusions of this work were published in their program summary documentation, the only document **not** considered export controlled by Boeing. From this work:

Detailed robustness analysis of various space-based architectures indicates that a commercial space-based CNS enhancement can provide very high availability and continuity characteristics. A five-satellite system with dual satellites at Atlantic and Pacific locations (fig. 3.5-10) provides U.S. domestic airspace and half of U.S. controlled oceanic airspace, including GOM and WATRS with triple-satellite coverage and 99.9987% availability. The far eastern Atlantic and far western Pacific oceanic regions receive dual-satellite coverage which provides 99.97% availability, much higher than current capability in oceanic airspace⁷³.

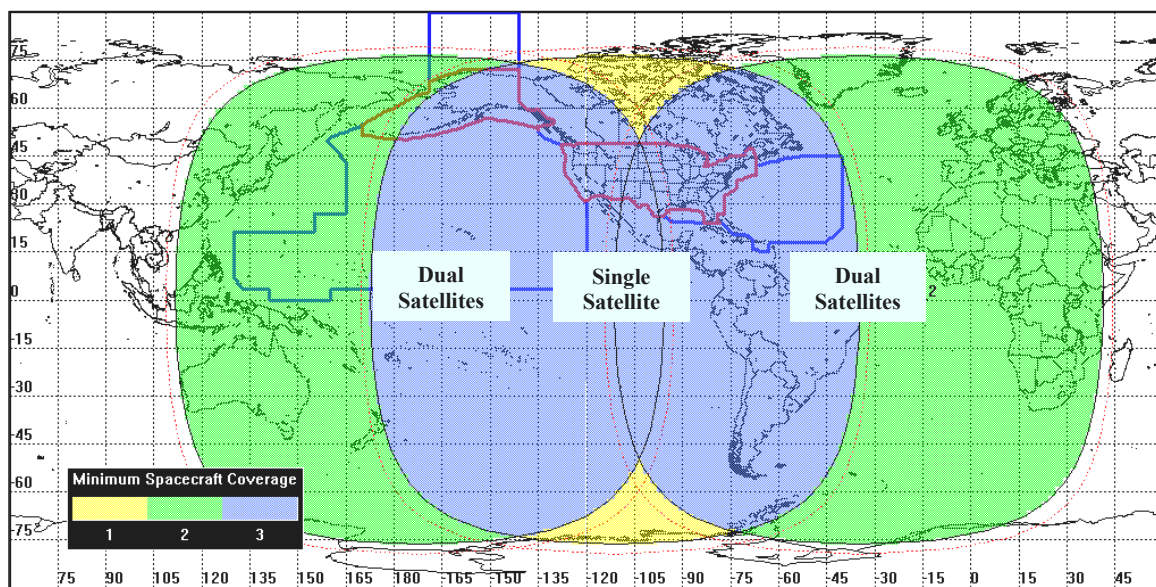


Figure 3.5-10: NAS-Wide Space-Based CNS Coverage with Commercial System⁷⁴

3.5.4.1.2 Avionics Discussion

Avionics, and in particular, avionics cost is a key constraint that limits the adoption and widespread deployment of satellite communication services. The SATCOM antenna accounts for a significant portion of the avionics cost. Industry is aware of this, and the Airlines Electronic Engineering Committee (AEEC) has recently started a project to create ultra compact and low cost SATCOM avionics. The AEEC APIM document provides the following background:

High prices for satellite equipment (as well as recurring service costs) have led most commercial air transport operators to install a SATCOM system only where required by regulatory agencies. It is used sparingly as a least preferred (from a cost standpoint) means of communications.

The myriad of form factors and wiring differences between avionics architectures has resulted in high charge for equipment and wiring provisions. In some instances airlines have had to support two SATCOM architectures because ARINC 741 equipment was too big for their small aircraft fleet.⁷⁵

The design goals of the ARINC APIM are to decrease cost (~\$150,000), weight, and size (6 MCU) of the avionics for use in Inmarsat BGAN SATCOM installations.

3.5.4.1.3 Latency and Call Setup Time Discussion

For some time, the NAS requirement for end-to-end voice latency has been 250 ms. Recent human factors investigations have indicated that some consideration should be given to relaxing that value.⁷⁶ There is at least some indication (based on the FAA transition team assignment of voice latency metrics, which is discussed elsewhere in this report) that the FAA might be willing to accommodate longer end-to-end latency values. The International Telecommunication Union (ITU) has considered this problem carefully, and provides the following guidance.

The ITU recommendation on Telephone Transmission Quality, Effect of Transmission Impairments, states that values of absolute delay for satellite facilities (approximately 300 ms in each direction of transmission) has little effect on the transmission quality of connections, provided talker and listener echo are adequately controlled⁷⁷.

The ITU Transmission Systems and Media, General Recommendations on the Transmission Quality for an Entire International Telephone Connection (ITU-T G.114) specification on one-way transmission time is:

0 to 150 ms	Acceptable for most user applications
150 to 400 ms	Acceptable provided that Administrations are aware of the transmission time impact on the transmission quality of user applications
above 400 ms	Unacceptable for general network planning purposes; however, it is recognized that in some exceptional cases this limit will be exceeded ⁷⁸

With this guidance, as long as a system was able to deliver latency performance of less than 400 ms end-to-end latency, its performance was not judged to be unacceptable. Those that could meet the current requirements were judged more favorably than those that could not.

From the above discussion, it should be clear that the real issue with satellite latency isn't voice quality, but call setup time. Figure 3.5-11 shows the SIP call setup in Proxy mode, which is likely the most efficient mode (there is also a redirect mode, but it would require more satellite hops). There are at least four transits between endpoint required, and setting up a call in less than a second would appear to be very difficult, even with SIP, which is a very efficient protocol. Long call setup times and party line operations are incompatible, and near instantaneous access to the channel is clearly the expectation of both the pilots and the controllers.

There are ways to mitigate these long call setup times. The most obvious is utilizing packet services, and IP multicast groups. With this architecture, the initiation delay is transferred to radio startup, and potentially to sector changes (the specifics of how sectors are configured and mapped into multicast groups will not be addressed in this report). This consideration alone would merit the recommendation that the satellite services used be the packet services, and that group conference calls (party line) be implemented via multicast groups.

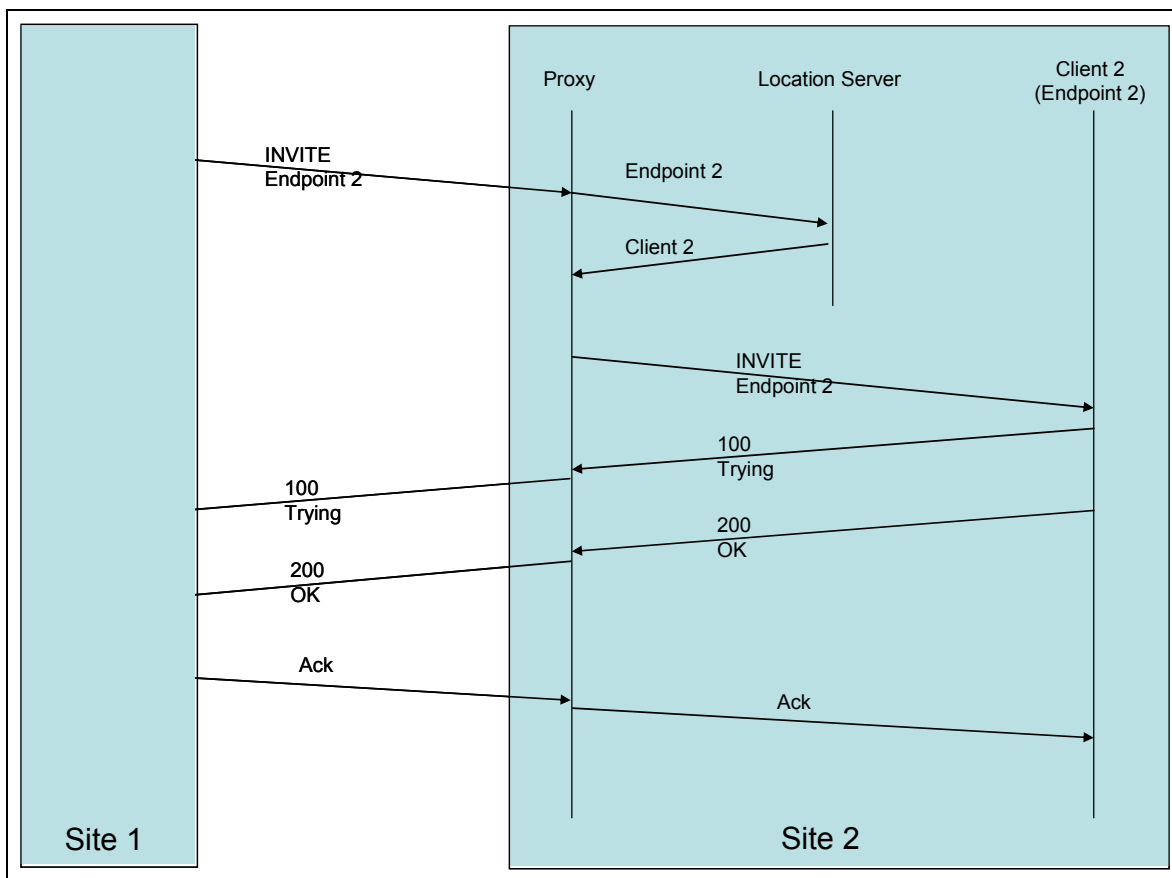


Figure 3.5-11: SIP Operation in Proxy Mode

3.5.4.2 Aero-BGAN Concept of Use

The use of Aero-BGAN for ATS and AOC communications is described in this section. As was provided for other technologies, the discussion will provide the applicable frequency band, applicable airspace environments, aeronautical communications services provided, Aero-BGAN services utilized, and architecture integration. The first four elements of this list are presented in table 3.5-5.

Table 3.5-5: Aero-BGAN Concept of Use Elements

Element	Proposed Value
Applicable Frequency Band	User communications at L-Band
Applicable Airspace Environments	Continental and Oceanic (excluding polar regions)
Aeronautical Communications Services Provided	<ul style="list-style-type: none"> • Pilot-Controller Voice: group conference, addressed, and broadcast • A/G and G/A addressed data • G/A broadcast data • Direct A/A communications
Applicable Aero-BGAN Services	Packet Data Services

Architecture Integration

A fundamental design criterion that must first be addressed is whether the Ground-Air communications are via the feeder link, or via the L-Band user data link. Referring back to figure 3.5-3, the normal mode of communications to the mobiles would be to access the BGAN Data Core Network via a point-of-presence. Data is transferred across the DCN to one of the two Satellite Access Stations, then up to the satellite via the feeder link, and down to the aircraft via the L-band spot beam. Figure 3.5-12 provides the physical architecture associated with this approach. An alternative, of course, is to establish both the uplink and downlink communications in the L-Band, so that the controller radio is no different (in function) than the aircraft radio, in that both are INMARSAT mobile subscriber terminals. Figure 3.5-13 provides the physical architecture associated with this approach.

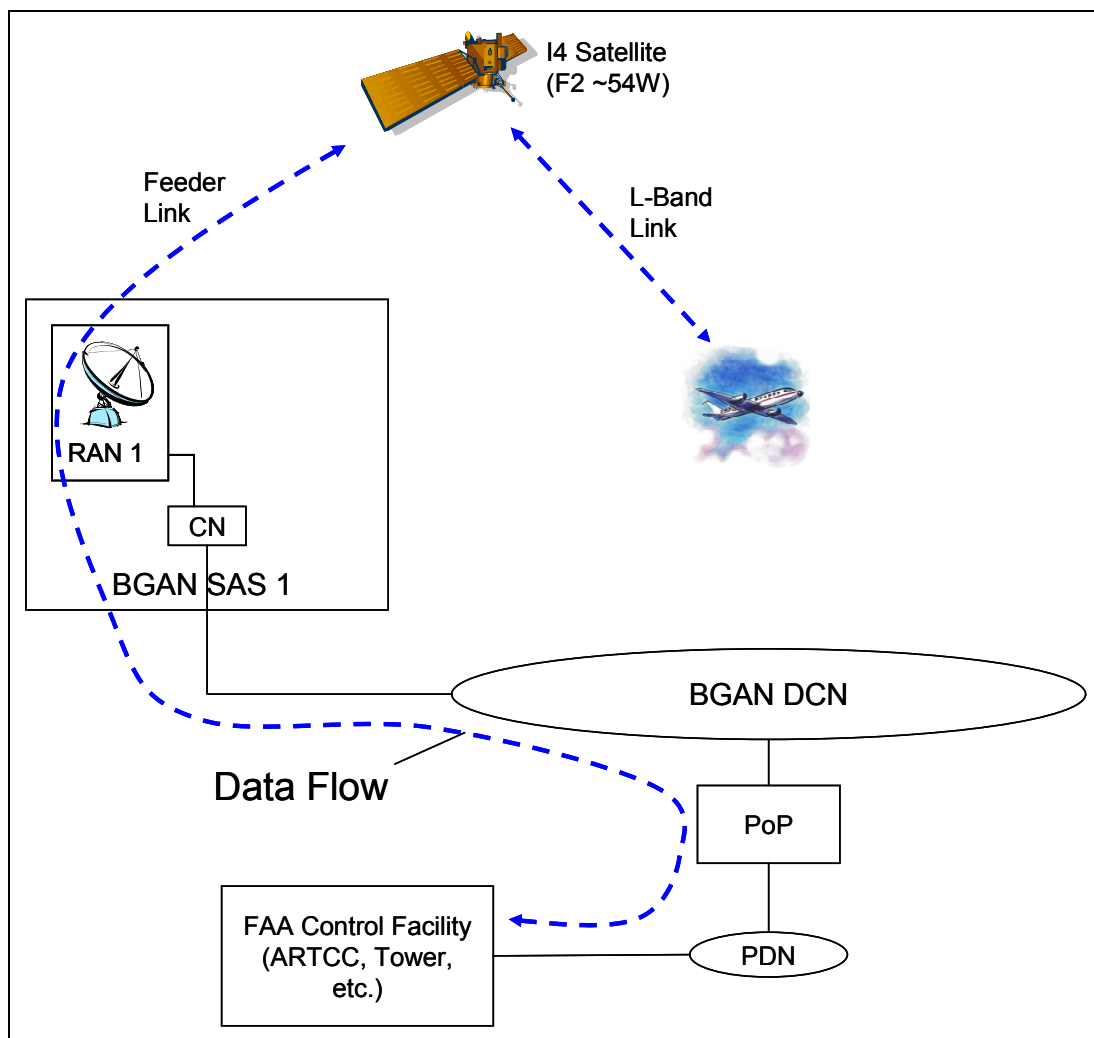


Figure 3.5-12: Notional Physical Architecture Using Aero-BGAN (Uplink on Feeder Link)

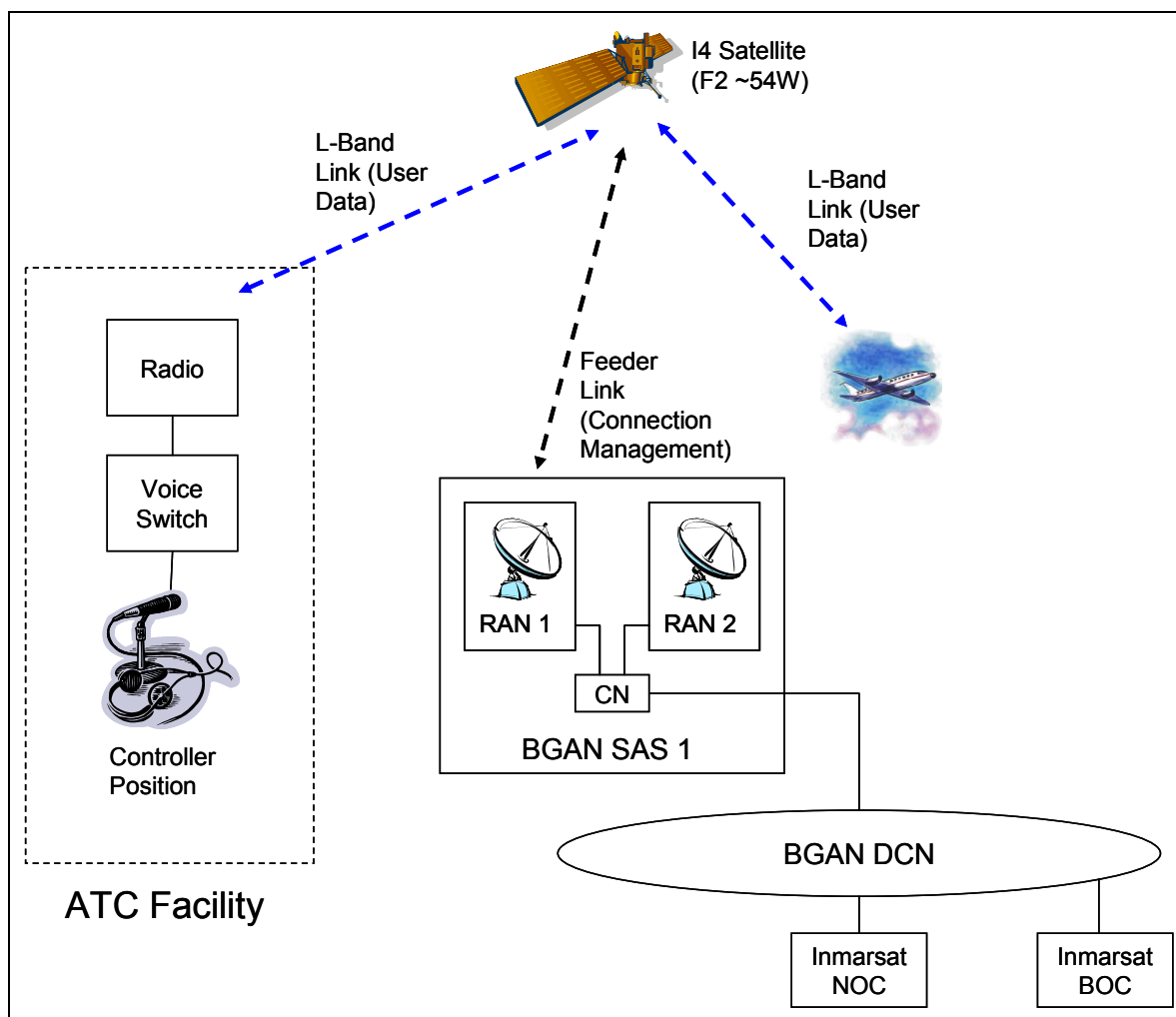


Figure 3.5-13: Notional Physical Architecture Using Aero-BGAN (Uplink on L-Band)

The two notional physical architectures both present some interesting discussion points involving cost of provisioning, and control of provisioning services. In the first (fig. 3.5-12), because neither Satellite Access Station (SAS) is in the U.S., connection to the Data Core Network would likely entail diverse oceanic leased line and associated costs necessary to establish diverse communications to the DCN. Having both SAS facilities in foreign countries necessitates a relinquishment of control that is likely not feasible for such an important function to our national security as Air Traffic Control. This architecture, while interesting, is not assumed to be implementable for ATS. It is, however, likely that this is the architecture that would be used to provision AOC communications by ARINC or SITA.

In the second (fig. 3.5-13), while the infrastructure appears simpler, and clearly the leased line TELCO costs will be reduced from both the current system and the first proposed system, the cost of satellite services would appear to be increased, as both the control site to satellite and satellite to aircraft links would be billed as satellite mobile calls. Further, the setup of multicast groups, authentication of users, and tracking of usage functions would still be required functions of the INMARSAT NOC and BOC. While this architecture has some reliance on foreign assets, it is perhaps possible to mirror some of the NOC and BOC functions in the US, though redundant oceanic attachments to the BGAN DCN. It is assumed that these institutional issues could be resolved, and that the architecture in figure 3.5-13 is the one that would be used.

In order to provide the quick call setup times required for party line operations, a voice over IP architecture using IP multicasting has been assumed. This requires that the SATCOM avionics be able to support VoIP functionality. This is how the service is envisioned to be used by Boeing as well, and they have done substantial work in specifying the avionics that would be required to implement this architecture. Figure 3.5-14 shows the Boeing concept of a SATCOM avionics architecture that supports Voice and Data over IP.⁷⁹

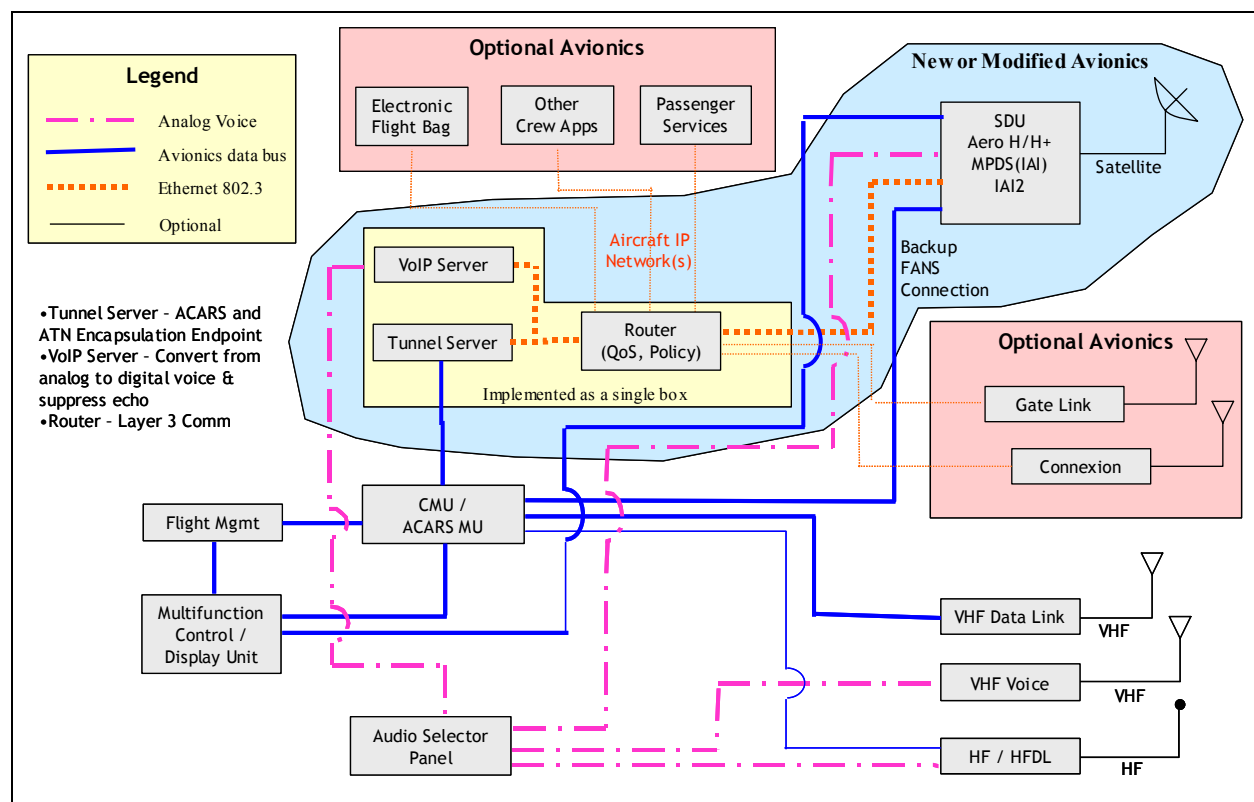


Figure 3.5-14: SATCOM Avionics Architecture for Voice and Data over IP

3.5.4.2.1 Aero-BGAN Availability, Avionics Cost, and Latency Discussion

The INMARSAT-4 constellation will not provide sufficient coverage overlap to meet the availability and continuity requirements for NAS critical communications (as was discussed in section 3.5.4.1.1). The INMARSAT-2 constellation (launched between 1990 and 1992 with a 10 year life expectancy) will have undoubtedly reached the end of its useful life by the beginning of the study time frame (2015). The INMARSAT-3 constellation (launched between 1996 and 1998, with a 13 year life expectancy) will be nearing the end of its useful life, or past the end of its useful life as well. This leaves one INMARSAT-4 satellite providing coverage over the entire continental United States (F2 at 53W over the Atlantic Ocean). Clearly, should INMARSAT remain in the satellite communications business, a fifth generation of satellites will be planned and launched, likely very close to coinciding with the start of the study time frame, but it seems very unlikely that the three overlapping satellite footprints would ever be provided.

In addition to concerns about the number of satellites, concerns exist about communications interruptions impacting the availability of this service due to communications overloading. Referring back to figure 3.5-4, the INMARSAT-4 53W satellite will provide about eight spot beams over the continental United States (six full beams and four additional half-beams). A Boeing analysis states, “*BGAN affords 240 kbps average throughput per channel with a maximum of ~16 channels per beam and ~60 channels per 7-beam reuse group.*”⁸⁰ This provides an average throughput of 15 Mbps for the airspace over the United States. Assuming that header compression is used, and that the vocoder used for this service is the DVSI AMBE vocoder that has been certified under the FAA NEXCOM program, a conservative estimate for a VoIP data stream would be 10 kbps. This would imply that 1,500 simultaneous conversations could be supported. However, in any one beam, this number would be reduced to a maximum of 384 conversations.⁸¹ Considering that one of the beams covers the entire northeast, this is probably a number that would likely lead to call blocking, which must be considered a contributor to service unavailability in accord with the methodology outlined in RTCA/DO-270 (see section C.4.2.4 for example).

The cost of certified avionics for use with Aero-BGAN will likely remain high. The published goal of the ARINC APIM for low-cost, small size, low weight Aero-BGAN avionics is to reduce costs to \$150,000. This figure is clearly out of the realm of affordability for General Aviation.

With the proposed architecture, voice latency and call setup times will likely be acceptable. They will certainly be much better than the current HF communications performance for Oceanic airspace. This technology seems to have a reasonable application to Oceanic airspace for ATS and AOC communications.

3.5.4.3 SDLS Concept of Use

The use of SDLS for ATS and AOC communications is described in this section. This discussion will provide the applicable frequency band, applicable airspace environments, aeronautical communications services provided, SDLS services utilized, and architecture integration. The first four elements of this list are presented in table 3.5-6.

Table 3.5-6: SDLS Concept of Use Elements

Element	Proposed Value
Applicable Frequency Band	User communications at L-Band
Applicable Airspace Environments	Continental and Oceanic (excluding polar regions)
Aeronautical Communications Services Provided	<ul style="list-style-type: none"> • Pilot-Controller Voice: group conference, addressed, and broadcast • A/G and G/A addressed data • G/A broadcast data • Direct A/A communications
Applicable SDLS Services	All of the specified SDLS services are applicable to aviation and would be implemented.

Architecture Integration

As was the case with Aero-BGAN, a fundamental design criterion that must first be addressed is whether the Ground-Satellite communications are via the feeder link, or via the L-Band user data link. The basic design of Mobile Subscriber Systems provides mobile connectivity to fixed terrestrial infrastructure as was shown in figure 3.5-12. Starting at the mobile (aircraft) communications is up to the satellite on the L-Band link, and then down to the ground gateway over the feeder link (typically C, or Ku-Band). From the ground gateway, connections are made into terrestrial networks, either telephony (PSTN) or packet, to the fixed ground infrastructure. This is the architecture that is documented in the SDLS Slice 3 Executive Summary. Thus the proposed physical architecture for evaluation of SDLS is shown in figure 3.5-15.

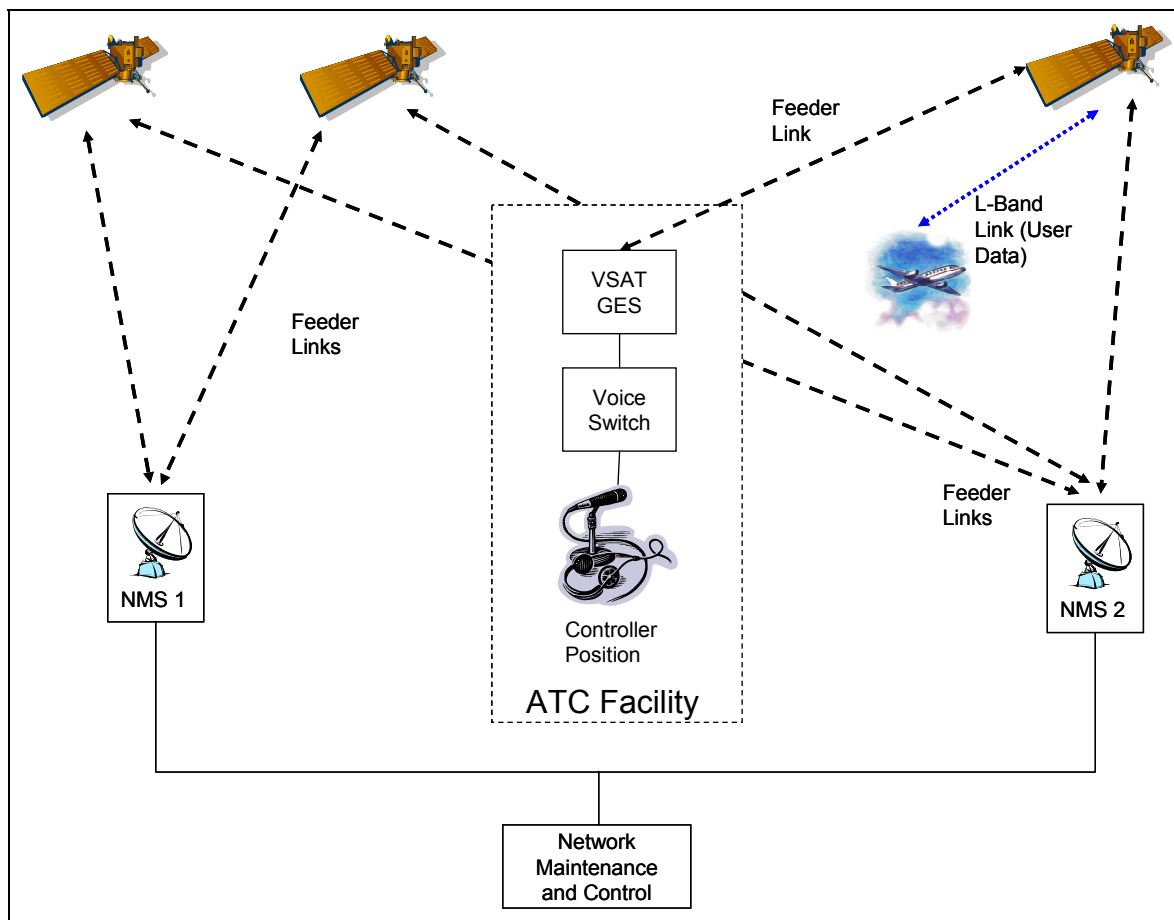


Figure 3.5-15: Envisioned SDLS Physical Architecture

In the notional architecture, the required FAA infrastructure improvements include the construction of two physically diverse satellite access points for network management and control of each satellite (labeled NMS, Network Management System, in the diagram for consistency with the SDLS documentation). These stations would be networked together with a third facility that would provide network monitoring and control. At each FAA facility, Ground Earth Stations would be constructed (SDLS documentation indicates that these could be Very Small Aperture Terminals, VSAT, at least in the Ku band) that interfaced with the facility voice switch and data networks to provide voice and data connectivity over the leased satellite bandwidth. The ground uplink transmissions would be on the feeder link. The satellite transponder would translate the C-Band feeder link data to L-Band and relay it to the AES on board the aircraft. This concept is illustrated in figure 3.5-16, which serves to illustrate the SDLS frequency plan.

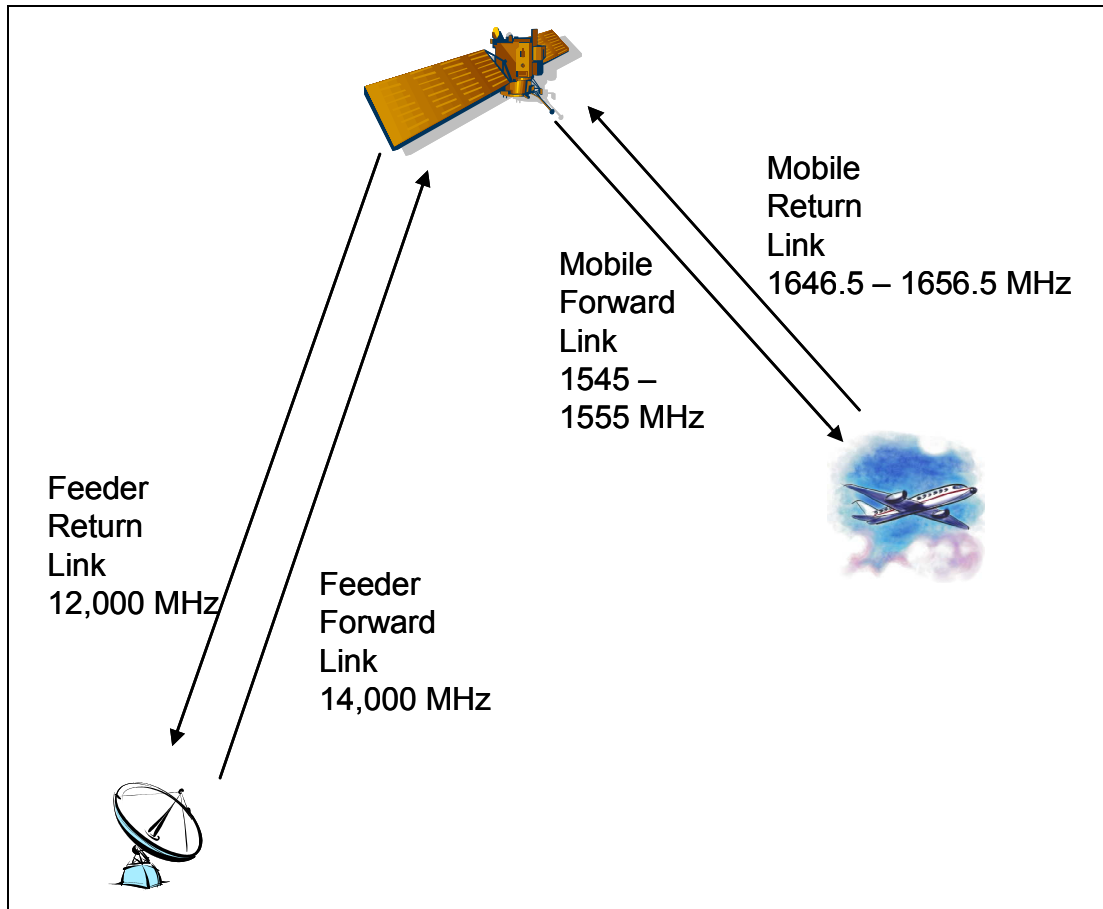


Figure 3.5-16: SDLS Frequency Plan

The SDLS documentation describes the delivery of voice on the “C” channel, which is a framed Raw CDMA carrier. This channel has reserved bandwidth, as SDLS defines a dedicated CDMA code for the “C” channel. Signals on this channel are framed. The framing provides 9600 bps for voice. Each voice frame is preceded by a unique 32 bit word, so that the data rate allocated to voice is 9120 bps. The DVSI AMBE vocoder would be used. SDLS presentations indicate that the expectation is to take the (already highly coded) DVSI packets and further code them with the rate $\frac{1}{2}$ turbo-coder that is defined as an element of the physical layer.⁸² Since all three classes of voice traffic are defined to be on the same “C” channel, it is assumed that there is sufficient bit space in the defined slot structure prior to this coding to define the Voice Class of Service. It is further assumed that packets that are marked as “Voice Service Class 3” (Party Line) are pulled from their slots and decoded by all of the aircraft in that talk group. Channel access would be negotiated by observation of the dedicated slots on the “C” channel.

3.5.4.3.1 SDLS Availability, Avionics Cost and Latency Discussion

The SDLS System as defined could provide the required availability for NAS Critical services *if* enough commercial satellites providing bandwidth at L-Band are available. A potential scheme would involve leasing bandwidth from Mobile Satellite Ventures (formerly AMSC) and INMARSAT. Mobile Satellite Ventures has two satellites in geostationary orbit that provide services at L-Band, and ambitious plans to launch two more.⁸³ The current Mobile Satellite Ventures satellites are at 101 and 106.5 degrees West Latitude. Coupled with the INMARSAT-4 53W satellite, the constraints of 3 overlapping coverage, independent look angles for Ionospheric Scintillation, and on-orbit sparing would all be met.

One of the published design goals of SDLS is to support several types of terminals, including low cost avionics terminals. Low cost terminals could be provided by reducing the antenna costs, which means specifying a simple omni-directional antenna instead of an adaptive array or gimbaled high-gain antenna. The trade, of course, is link margin. An omni-directional antenna can only support low data rates and still close the satellite link. Basic SDLS terminals have a passive low gain antenna (0 dBi at 5° of elevation), an air cooled HPA (40W), and provide a nominal data rate of 5.5 kbps. The design target is that the price of the SATCOM terminal would be comparable to a VHF terminal.

Finally, voice latency and call setup times will likely be acceptable because of the use of dedicated bandwidth (the “C” Channel) to provide a party line.

3.5.4.4 *Iridium Concept of Use*

The use of Iridium for ATS and AOC communications is described in this section. This discussion will provide the applicable frequency band, applicable airspace environments, aeronautical communications services provided, SDLS services utilized, and architecture integration. The first four elements of this list are presented in table 3.5-7.

Table 3.5-7: Iridium Concept of Use Elements

Element	Proposed Value
Applicable Frequency Band	User communications at L-Band
Applicable Airspace Environments	Continental and Oceanic (including polar regions)
Aeronautical Communications Services Provided	<ul style="list-style-type: none"> • Pilot-Controller Voice: group conference, addressed, and broadcast • A/G and G/A addressed data • G/A broadcast data • A/A communications
Applicable Iridium Services	Iridium Packet and Voice services

Architecture Integration

Two potential Iridium architectures are described in this section. The first, “Iridium Netted Radio,” was described in a response to a NASA Request for Information by General Dynamics Decision Systems and has been used in the Alaska Capstone project to demonstrate proof of concept. A second architecture, termed the “Dedicated Circuit” architecture was also described in a response to a NASA Request for Information by Raytheon. Both concepts are described below, first the Iridium Netted Radio concept, then the Dedicated Circuit concept. The concept that was selected for evaluation, and the rationale for that selection is then described.

The Iridium Netted Radio architecture has three architectural elements, the Group Radio Controller (ground infrastructure), the Iridium Netted Radios (avionics), and the Iridium Satellite system. The Group Radio Controller would be provisioned by the Civil Aviation Authority, either at an Iridium gateway, or, at an Air Traffic Control services control site. The Group Radio Controller manages system resources, and is a key component of the architecture, in that it keeps track of the connected aircraft, their assigned slots, and their assigned channels. Figure 3.5-17 provides an overview of the Iridium Netted Radio architecture.

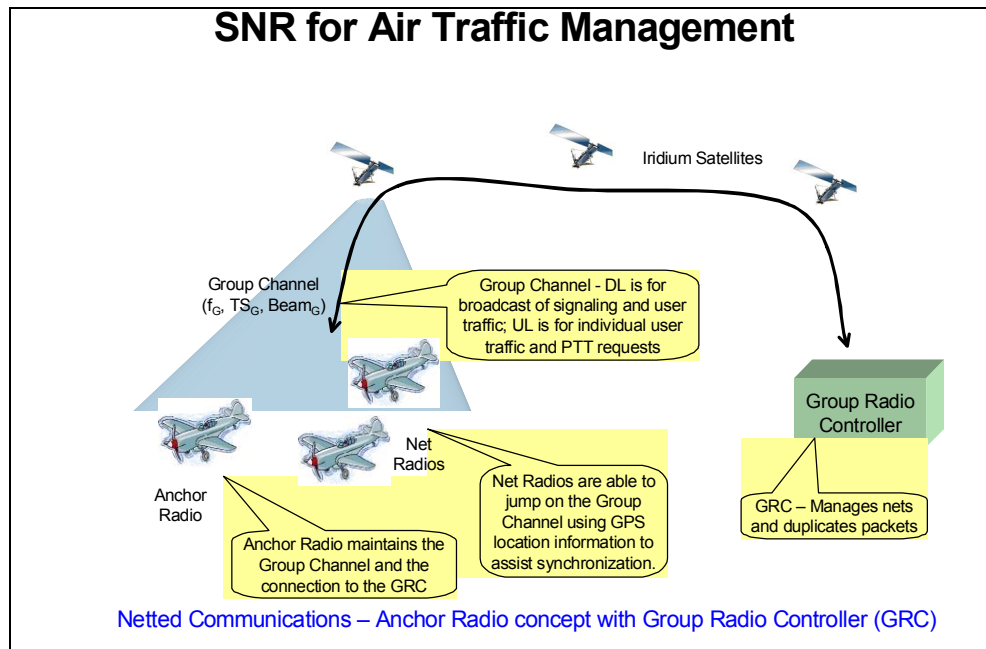


Figure 3.5-17: Iridium Netted Radio Architecture⁸⁴

The Iridium Netted Radio concept of operation is as follows. The first aircraft, called the Anchor aircraft (each talk group requires an Anchor aircraft), calls the Gateway and requests a channel with the Ground Resource Controller. By convention, the assigned channel is called Channel 1. At the completion of the (Iridium plus Ground Resource Controller protocol) call setup process, the call between the Anchor aircraft and GRC is established on channel 1. The Ground Resource Controller assigns a slot to the Anchor aircraft for use in transmitting data (this concept was used to demonstrate ADS functions in the Capstone project, so a regular reporting of position data was envisioned as a central element of the concept, but clearly other data messages, albeit short could be sent in these slots as well). The Anchor aircraft can now use the provisioned channel for both voice and data.

For a second (or any subsequent) aircraft to join the network, it must first establish a call to the Ground Resource Controller on a separate Iridium channel (not channel 1) through the Iridium Gateway. This channel is established between the aircraft and the Ground Resource Controller for the purposes of “Net Entry” and it is eventually dropped. After call setup on the second channel, the Ground Resource Controller assigns a slot to the new aircraft on channel 1, and causes the aircraft avionics to tune to this channel. The new net participant is now sharing Ch 1 with Anchor aircraft. This process will go on until a pre-determined, maximum number of aircraft are sharing the channel. The data rate that can be achieved by the Iridium Netted Radio concept is low, but it does provision a party line, with operational behavior that seems identical to the current VHF analog radio system.

The “Dedicated Circuit” notional Iridium physical architecture is presented in figure 3.5-18. In this architecture, dedicated FAA circuits are provided for each sector, with each of the circuits being made continuous across the satellites by installing bridging equipment in the Iridium gateway (located in Tempe, AZ). The FAA control facility equipment includes multiple satellite transceivers (and antennas), all interfaced to the facility voice switch and data network through a data multiplexing element. The ground uplink and downlink are both in L-Band with this implementation. Dedicated party-line voice is provided with this architecture. If several channels are bonded together, than data rates that are adequate for the basic data needs can be achieved, although this will come at some financial cost.

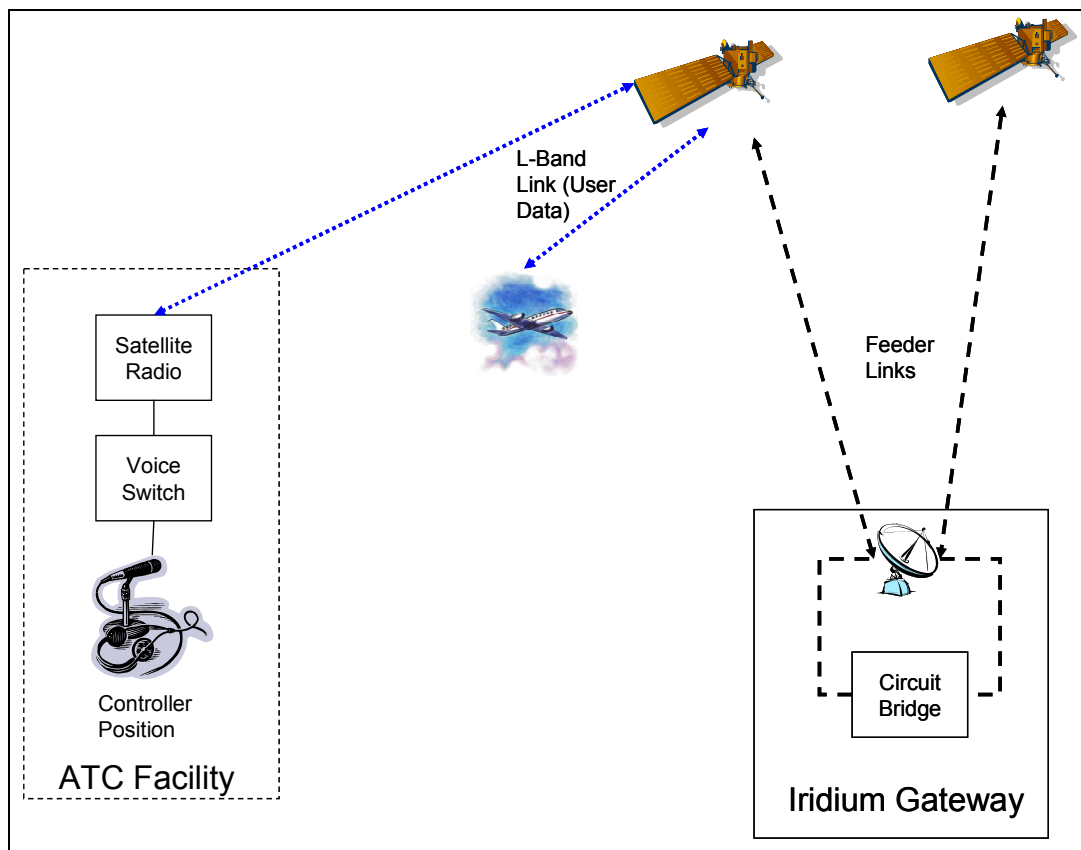


Figure 3.5-18: Notional Iridium Physical Architecture

The “Dedicated Circuit” architecture was selected for evaluation, as opposed to the Iridium Netted Radio, with the following rationalization. The Iridium system provides a very low data rate per channel, and the assignment of dedicated slots to the entrants of a net in the Netted Radio concept further reduces this rate. While this is fine for the primary intention of the concept (dissemination of position information through regularly scheduled broadcasts) it does not provide the throughput rates that were required of basic data in the pre-screening criteria. A second and more serious consideration is the incidence of dropped calls in the Iridium system. Iridium performs system testing on a weekly basis from its Tempe Arizona gateway. Among the system parameters that are measured are call setup percent completion, and the percentage of dropped calls (calls are maintained for a certain duration for the purposes of the tests, and on occasion a satellite handoff results in a dropped call). Published results of this testing indicate that for 8,590 weekly test calls, a small, but significant number of dropped calls are measure, corresponding to a 0.6% call drop rate.⁸⁵

The assumption that calls are primarily dropped because of missed handovers is why the “Dedicated Circuit” architecture was evaluated instead of the Iridium Netted Radio architecture. Extending the Iridium measured statistics would indicated that some amount of sector outages could be anticipated when using the Iridium Netted Radio concept, as the circuit that had been setup between the Anchor aircraft and the Ground Resource Controller was handed off, and occasionally dropped. These dropped calls would

affect all of the aircraft in the sector, and result in a loss of communications to the sector that would likely be deemed unacceptable for critical communications. (Recall that critical communications can have outages of six seconds no more than every six months.) Because the Iridium call setup time is long, and each and every aircraft must go back through this process to restore the net, the total outage duration would likely be both too long and too frequent. The “Dedicated Circuit” approach, with its nailed up circuits and absence of handoffs would not suffer from the frequency of dropped Iridium calls.

3.5.4.4.1 Iridium Availability, Avionics Cost and Latency Discussion

Availability. The Iridium System as defined will not provide the necessary availability for NAS critical services. Catastrophic satellite failures will result in moving coverage holes. While the size of the hole can be minimized by turning on more of the adjacent satellites spots, the holes cannot be completely closed by this mechanism. On-orbit spares exist, and Iridium has plans to replenish their constellation, but the replacement of a defective satellite requires the maneuvering of an on-orbit spare to the right orbital slot, which can take hours, or even days.

Cost. Currently, Iridium single channel radios suitable for GA installations cost on the order \$15,000 for single channel and \$42,000 for dual channel models. The cost of avionics should not be a problem with Iridium. This is in part due to its low earth orbit, and in part due to its low data rate. The combination of these factors allows the satellite link to be closed with cheap omni-directional antennas. The simplicity of the air interface simplifies receiver design. The demonstrated consequence is low cost avionics.

Latency. The Iridium voice latency is good (less than 250 ms, even with multiple satellite to satellite hops. Since the specified architecture requires no inter-satellite hops, the latency performance should be quite good.) The Iridium call setup time is long, and necessitates the bridging approach outlined below for implementing a party line. To implement a party line, all of the users in a given sector would share a single voice “channel”. This channel would be implemented as a single dedicated circuit in each satellite beam (a circuit for all of the eleven satellites in the orbital plane) that supports users in the sector (every sector would require its own dedicated set of circuits). The collection of dedicated circuits would then be tied together using a bridging function in the gateway. This bridging function would be required to support both dynamic sector memberships and the movement of the satellite constellation relative to the members of the sector. The shared channels would be continuously dedicated to the FAA.

3.5.5 Evaluation Summary and Scores

Table 3.5-8 provides the scoring summary for Aero-BGAN. The rationale for the assigned scores is provided in table 3.5-9.

Table 3.5-8: Aero-BGAN Evaluation Worksheet

	Criteria	Surface	Terminal	En Route	Oceanic	Polar
Voice Needs	1					
Pilot-Controller Talk Group	1A1					
Pilot-Controller Selective Addressing	1A2					
Direct Pilot-Pilot	1A3					
Broadcast capability	1A4					
Capacity provided	1B1					
Address space	1B3					
Aircraft mobility management	1C1					
Latency	1C2					
Basic Data Needs	2					
A/G and G/A Addressed Data Transport	2A1					
Ground-to-Air Broadcast Data Transport	2A2					
Aggregate Data Rate	2B1					
Number of Users	2B2					
Uplink and Downlink Priority Levels / QoS	2C1					
Latency	2C2					
Enhanced Data	3					
ADS-B	3A1					
Pilot-Pilot Data Transport	3A2					
Aggregate Data Rate	3B1					
Technology Readiness Level	4					
Standardization Status	5					
Certifiability	6					
Ground Infrastructure Cost	7					
Cost to Aircraft	8					
Spectrum Protection	10					
Security	11					
Transition	12					

Table 3.5-9: Aero-BGAN Scoring Rationale

Element	Score	Rationale
Pilot-Controller Talk Group	Green (S, T, E, and O) Red (P)	The NexSAT mission requirements require party line functionality. It is assumed that this system will provide this functionality.
Pilot-Controller Selective Addressing	Green (S, T, E, and O) Red (P)	It is virtually certain that this service will be provided as a native capability.
Direct Pilot-Pilot	Yellow (S, T, E, and O) Red (P)	Accomplish via satellite intermediary (re-broadcast).
Broadcast capability	Green (S, T, E, and O) Red (P)	Satellite services provide ideal broadcast functionality.
Capacity provided	Yellow (S, T, and E) Green (O and P)	There are about 8 spot beams over CONUS. Analysis indicates this will provide 15 Mbps capacity or roughly 1500 voice conversations. This probably does not support a 'notional doubling'. A notional doubling would be supported in remote regions, so green was assigned to oceanic regions.
Address space	Green	Should provide sufficient address space
Aircraft mobility management	Green (S, T, E, and O) Red (P)	Native function Polar gets red because BGAN does not provide polar coverage.
Latency	Yellow (S, T, and E) Green (O and P)	Voice latency is on the order of 400 ms (due to VoIP over GEO).
A/G and G/A Addressed Data Transport	Green (S, T, E, and O) Red (P)	Native function.
Ground-to-Air Broadcast Data Transport	Green (S, T, E, and O) Red (P)	Native function.
Aggregate Data Rate	Green	Supports high data rates.
Number of Users	Green	There is no limit for the packet service model.
Uplink and Downlink Priority Levels/QoS	Green	Will support QoS and prioritization
Latency	Green	Assume that the service will meet the requirements as specified in "New Generation Satellite Communication Systems(s) Mission Requirements," EWP Deliverable Reference Number D4B
ADS-B	Red	It seems highly unlikely that ADS-B could be provided with this technology
Pilot-Pilot Data Transport	Yellow (S, T, E, and O) Red (P)	Provides air-to-air data with an intermediary. No polar coverage.
Aggregate Data Rate	Yellow (S, T, E, and O) Red (P)	Provides data rates up to 432 kbps.
Technology Readiness Level	Yellow	Since satellites are not deployed, rated this as a TRL 4. However, it could be argued that since Regional BGAN is operational, the rating should be a TRL 5.
Standardization Status	Yellow	Standards and Recommended Practices applicable to the use of next-generation satellite system (NGSS) communications technologies to support the aeronautical mobile-satellite (R)* service (AMS(R)S)—appendix is required to standardize this
Certifiability	Yellow	Being designed for safety-related service
Ground Infrastructure Cost	Yellow	Satellite capacity is leased so initial investment is small. However leasing a substantial capacity of satellites will be expensive, but the use of the packet service model should mitigate such costs.
Cost to Aircraft	Red	The ARINC APIM has a goal of producing avionics at a price point of \$150,000. This is the most costly avionics solution by a large factor.
Spectrum Protection	Green	L-Band AMS(R)S spectrum
Security	Green	Aero-BGAN provides authentication and integrity.
Transition	Green	Supports incremental deployment

Table 3.5-10 provides the scoring summary for SDLS. The rationale for the assigned scores is provided in table 3.5-11.

Table 3.5-10: SDLS Evaluation Worksheet

	Criteria	Surface	Terminal	En Route	Oceanic	Polar
Voice Needs	1					
Pilot-Controller Talk Group	1A1					
Pilot-Controller Selective Addressing	1A2					
Direct Pilot-Pilot	1A3					
Broadcast capability	1A4					
Capacity provided	1B1					
Address space	1B3					
Aircraft mobility management	1C1					
Latency	1C2					
Basic Data Needs	2					
A/G and G/A Addressed Data Transport	2A1					
Ground-to-Air Broadcast Data Transport	2A2					
Aggregate Data Rate	2B1					
Number of Users	2B2					
Uplink and Downlink Priority Levels / QoS	2C1					
Latency	2C2					
Enhanced Data	3					
ADS-B	3A1					
Pilot-Pilot Data Transport	3A2					
Aggregate Data Rate	3B1					
Technology Readiness Level	4					
Standardization Status	5					
Certifiability	6					
Ground Infrastructure Cost	7					
Cost to Aircraft	8					
Spectrum Protection	10					
Security	11					
Transition	12					

Table 3.5-11: SDLS Scoring Rationale

Element	Score	Rationale
Pilot-Controller Talk Group	Green (S, T, E, and O) Red (P)	This is specified as a supported bearer service
Pilot-Controller Selective Addressing	Green (S, T, E, and O) Red (P)	This is specified as a supported bearer service
Direct Pilot-Pilot	Yellow (S, T, E, and O) Red (P)	Accomplish via satellite intermediary (re-broadcast).
Broadcast capability	Green (S, T, E, and O) Red (P)	Satellite services provide ideal broadcast functionality.
Capacity provided	Yellow (S, T, and E) Green (O and P)	Without custom built satellites with a large number of spot beams, the additional communications capability provided will not be equivalent to a "notional doubling". A notional doubling would be supported in remote regions, so green was assigned to oceanic regions.
Address space	Green	Should support this
Aircraft mobility management	Green (S, T, E, and O) Red (P)	Should support this
Latency	Yellow(S, T, and E) Green (O and P)	The demonstration unit voice latency was less than 400 ms. The operational system should provide latencies greater than 250 ms, but less than 400 ms. This is based on a notional latency budget of 240 ms for the satellite hop, 80 ms for the DVSI AMBE vocoder, and 40 ms for Telco and ground/aircraft processing. The "C" channel slot delay should be less than 40 ms. Call setup is likely to be longer than ICOCR threshold. While the QoS specification says "always on," the demonstration unit reports measurements of 3.7 and 4.5 seconds (direction dependent).
A/G and G/A Addressed Data Transport	Green (S, T, E, and O) Red (P)	This is specified as a supported bearer service
Ground-to-Air Broadcast Data Transport	Green (S, T, E, and O) Red (P)	This is specified as a supported bearer service
Aggregate Data Rate	Yellow (S, T, and E) Green (O and P)	Provides 5.5 kbps per aircraft. Higher data rates possible with higher gain antennas. However, without a large number of spot beams, it isn't clear how this service could be provided for a large number of AC. The concept document claims that 2000 AC could be supported with throughput of 150 bps
Number of Users	Green	Should support this
Uplink and Downlink Priority Levels/QoS	Green	Demonstration and system design both support QoS
Latency	Green	Demonstrator meets all ATN performance level requirements (A-J)
ADS-B	Red (all domains)	ADS-B is not a part of the SDLS system concept. The technology will likely not support this.
Pilot-Pilot Data Transport	Yellow (S, T, E, and O) Red (P)	Provides air-to-air data with an intermediary.
Aggregate Data Rate	Red (all domains)	Does not support larger data requirements
Technology Readiness Level	Yellow	While the existence of a demonstration unit would seem to merit a TRL 6 (System/subsystem model or prototype demonstration in a relevant environment), the immaturity of the physical layer description and specifically of the end-to-end protocol architecture results in this being graded as a TRL 5.
Standardization Status	Yellow	AMSS SARPS exist. The demonstrator was shown to have better performance than required in the SARPS. Development of an Appendix to DO-262 would be required.
Certifiability	Yellow	SDLS is being developed specifically for the aviation industry.
Ground Infrastructure Cost	Red	Requires large initial investment. If satellite capacity is leased, network management and ground station infrastructure still has to be developed and leasing a substantial capacity of satellites will be expensive. If satellites are procured, this cost of development, launch, insurance etc. is high.
Cost to Aircraft	Green	Low cost Avionics
Spectrum Protection	Green	Proposed to operate in protected L-band spectrum
Security	Green	SDLS provides authentication and integrity.
Transition	Red	Requires large initial investment. While satellite capacity could be leased, network management and ground station infrastructure still has to be developed.

Table 3.5-12 Table 3.5-12 provides the scoring summary for Iridium. The rationale for the assigned scores is provided in table 3.5-13.

Table 3.5-12: Iridium Evaluation Worksheet

	Criteria	Surface	Terminal	En Route	Oceanic	Polar
Voice Needs	1					
Pilot-Controller Talk Group	1A1					
Pilot-Controller Selective Addressing	1A2					
Direct Pilot-Pilot	1A3					
Broadcast capability	1A4					
Capacity provided	1B1					
Address space	1B3					
Aircraft mobility management	1C1					
Latency	1C2					
Basic Data Needs	2					
A/G and G/A Addressed Data Transport	2A1					
Ground-to-Air Broadcast Data Transport	2A2					
Aggregate Data Rate	2B1					
Number of Users	2B2					
Uplink and Downlink Priority Levels / QoS	2C1					
Latency	2C2					
Enhanced Data	3					
ADS-B	3A1					
Pilot-Pilot Data Transport	3A2					
Aggregate Data Rate	3B1					
Technology Readiness Level	4					
Standardization Status	5					
Certifiability	6					
Ground Infrastructure Cost	7					
Cost to Aircraft	8					
Spectrum Protection	10					
Security	11					
Transition	12					

Table 3.5-13: Iridium Scoring Rationale

Element	Score	Rationale
Pilot-Controller Talk Group	Green (all domains)	Concept of group conference is based on designs which have been developed under DoD; Iridium indicates that General Dynamic Decision Systems are working on a PTT voice capability over Iridium that would provide broadcast call features.
Pilot-Controller Selective Addressing	Green (all domains)	Native capability
Direct Pilot-Pilot	Yellow (all domains)	Support air-to-air voice via satellite intermediary.
Broadcast capability	Green (all domains)	Can broadcast to everyone in the group conference
Capacity provided	Yellow (S, T, and E) Green (O and P)	Implementation of group conference with dedicated circuits limits the final capacity of this system in regions that have a large number of aircraft. Based on the system design of 240 channels, each having 4 slots (channels)
Address space	Yellow (S) Green (T, E, O, and P)	This is not infinitely scaleable and has an absolute bound over a geographic area: e.g., could not support more than 5 talk groups of 200 users in one satellite. There is a hard upper limit on the broadcast functionality provided.
Aircraft mobility management	Green (all domains)	Native capability
Latency	Green (all domains)	Latency is less than 250 ms
A/G and G/A Addressed Data Transport	Green (all domains)	Native capability
Ground-to-Air Broadcast Data Transport	Green (all domains)	Can broadcast to everyone in the group conference
Aggregate Data Rate	Green (all domains)	2.4 kbps per user scales to 192 kbps for a spot beam (this assumes a nominal 80 channels per spot beam). While the 2400 bps/channel data rate is quite low, the basis of evaluation for this criterion is the aggregate data rate provided by a technology for a user group. From the evaluation criteria: "Green—Greater than or equal to 31.5 kbps per user group (per MACONDO rate estimate)."
Number of Users	Green (T, E, O, and P) Yellow (S)	This is not infinitely scaleable and has an absolute bound over a geographic area: e.g., could not support more than 5 talk groups of 200 users in one satellite. There is a hard upper limit on the broadcast functionality provided.
Uplink and Downlink Priority Levels/QoS	Yellow (all domains)	Does not do QoS
Latency	Yellow (all domains)	Low data rate channels and lack of QoS leaves doubt that this could provide the required latency under load
ADS-B	Red (all domains)	Can't support air-to-air with no intermediary.
Pilot-Pilot Data Transport	Yellow (all domains)	Support air-to-air voice via satellite intermediary.
Aggregate Data Rate	Green (O and P) Yellow (S, T, and E)	Should be able to provide up to 600 kbps for a single 560 km spot beam
Technology Readiness Level	Green	Being used in Capstone and by Aircell
Standardization Status	Yellow	MASPS and SARPS for advance satellite systems—appendix is required to standardize this
Certifiability	Red	Iridium is not designed and developed to a safety standard
Ground Infrastructure Cost	Yellow	While required ground infrastructure is small, substantial recurring costs may be required for leasing
Cost to Aircraft	Green	Estimated cost is comparable to ARINC 716 8.33/25 kHz DSB-AM analog receiver
Spectrum Protection	Green	The frequency band 1 610 to 1 626.5 MHz is allocated to the aeronautical mobile-satellite (R) service on a primary basis, subject to international agreement obtained under No. 9.21
Security	Green	Assume that there are proprietary methods employed to validate handsets.
Transition	Green	Supports incremental deployment

3.5.5.1 Technology benefits and issues, and evaluation summary

There are issues associated with satellite communications that make the technology difficult to apply to a safety of life service requiring five nines of availability. These obstacles can be overcome, albeit at some

cost. The identified obstacles include availability, terminal cost (and size), call latency, call setup times, and maneuvering (antenna shielding from aircraft banking) induced service interruptions.

In general, satellite technology works best for broadcast services, and communications to remote regions. Maps of call originations to Mobile Satellite Providers show the densest areas of call origination along the coasts, by maritime users; and from remote inland areas. Figure 3.5-19 shows a map of call origination locations to illustrate this phenomenon. While it can be seen that there are a large number of calls originating from the North American land mass, the percentage of satellite calls to cellular calls from this same area is small.

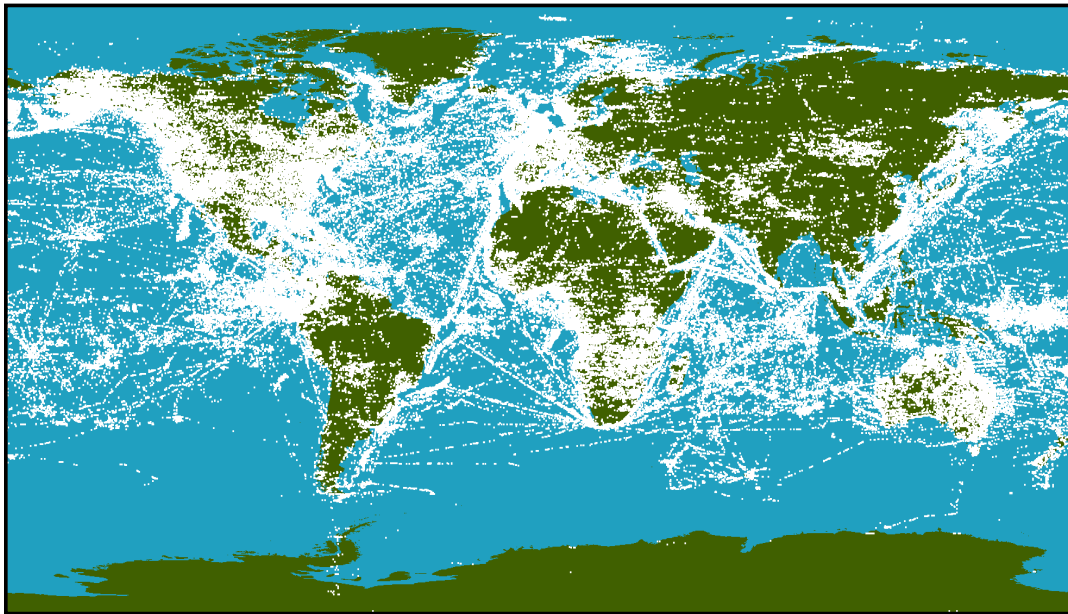


Figure 3.5-19: Call Origination Locations (typical month) for a Mobile Satellite Provider

Satellite technology would appear to have three potential benefits to the provisioning of A/G aeronautical communications:

- Use of satellite communications to oceanic and polar regions (where coverage can be obtained) makes sense, and is most likely the best and most effective way to communicate in these regions
- Use of satellites to provide broadcast services to large geographic areas. This use of satellites is well understood, and has successful business models, primarily in the Television and Radio industries. Satellites would be used to augment terrestrial communications and provide broadcast services, which might include weather and other advisory communications.
- A potential next generation communications system might use high data rate, broadband systems in the terminal area, and around densely populated regions, but satellites for coverage of en-route domains with historically sparse aircraft densities. This would follow many ground infrastructure models, and makes sense from a cost of provisioning standpoint.

None of the technologies that were evaluated scored well. Aero-BGAN provides good voice and basic data services and marginal enhanced data (no ADS-B support and limited capacity). However, it is not able to supply the notional doubling of voice capacity that is a desired feature of the new system, and its avionics costs will likely remain high. SDLS provides good voice and data services, but will also not provide the notional doubling of voice capacity. The low data rate provided by SDLS impacts its basic and enhanced performance, as it was judged to not supply a sufficient aggregate data rate. Further, based on the apparent requirement to construct a Network Management System for each of the leased commercial satellites employed in the SDLS space segment, the ground infrastructure cost was judged to

be high. Iridium provides good voice and data services, but its capacity is low, and dedicating circuits from all 11 satellites in an orbital plane for each sector that is provisioned exacerbates this problem.

In examining the particular technologies, the following observations are offered. The use of Aero-BGAN for sole-source provisioning of en-route communications over the Continental United States is not recommended. It is unlikely that the INMARSAT satellite constellations will provide sufficient redundancy to meet the requirements for critical communications. Further, avionics costs will likely remain too high for applicability to general aviation.⁸⁶ Consequently, this technology is likely restricted to the Oceanic and Polar domains or used as an augmentation to some other FCS technology.

Iridium seems to be a very useful system, with its low latency and global coverage. However, the data rate that it provides is low, and it likely can not meet the FAA availability requirements for critical NAS services. A potential augmentation to Iridium that would enable it to meet availability requirements is to provide the backup services over geostationary satellites. This is very similar to how some of the Remote Communications Air-Ground (RCAG) telecommunications were provisioned for space diversity, with commercial leased land-line circuits providing the primary means of communications, and geosynchronous telecommunications circuits providing the backup circuits. (In a very real sense, the FAA has been using satellites for A/G communications for some time. However, in these instances, there has just always been a terrestrial path in place.) Regardless, the concept of permanent bridged circuits being available for exclusive FAA use would seem to provide good voice performance, and likely should be investigated.

The SDLS concept might have some promise, but it is not mature and requires Civil Aviation Authority development and infrastructure investment. Despite the fact that it was rated poorly on data capacity, the data capacity of the solution can be scaled, simply by leasing more satellite bandwidth and installing more GES. The GES cost will likely be cheap, as (especially for Ku band feeder links) VSAT technology could be employed. Once the Network Management System has been built, incremental SDLS costs will be low, and the recurring costs of leasing bandwidth will dominate the system costs. As an example SDLS implementation, the FAA could lease bandwidth from the Mobile Satellite Ventures (formerly AMSC) satellites, located at 101 and 106.5 degrees west, and INMARSAT I-4 satellite, to be located at 53 degrees west. This implementation would meet the availability constraints of NAS critical services, by providing satellites with diverse look angles and an on-orbit spare. This technology, if used in conjunction with a high data-rate broadband technology in the terminal area, provides a potentially good hybrid solution.

3.6 Custom Narrowband VHF

The narrowband VHF systems which were considered in this section are all presently VHF sub-networks designed, or adapted, for aviation. No commercial systems fell into this category beyond those designed for aviation.

3.6.1 Overview of the Family

The custom narrowband VHF family includes standard narrowband VHF systems already developed for application to AOC, ATS, and/or ATC services, some proposed variants to an existing system, and a proposed system for application to AOC, ATC, and ADS-B services. The standard set consists of three systems developed and approved as VHF sub-networks through ICAO with published Standards and Recommended Practices (SARPS). These standard systems are:

- Mode 2, an AOC and ATS data-only system with demonstrated ATC usage through CPDLC
- Mode 3, an ATC system providing both voice and data
- Mode 4, a surveillance data-only system being developed for point-to-point data

These systems were identified for evaluation from a review of existing, including non-aviation-related, communications services. IP over Mode 2 was proposed by SITA through the RFI process. Additional

systems solicited through the RFI process resulted in three more systems, two of which are actually variations of the Mode 3 system. They are:

1. Mode 3 with Single Antenna Interference Cancellation (SAIC)
2. Mode E (a modification of Mode 3 with 8.33 kHz spacing)
3. E-TDMA

Mode 3 with SAIC was proposed as a means of increasing channel capacity through use of a receiver signal processing enhancement. Mode E was conceived and proposed by Rockwell-Collins as an 8.33 kHz scheme with the flexibility of either a voice and/or data capability. E-TDMA is an enhanced form of Time Division Multiple Access proposed by the ATM department of the *SOFREAVIA Group*, a French aviation engineering company which submitted its concept through the RFI process. Of all these systems, presently only Mode 3, Mode 3 with SAIC, and Mode E provide both voice and data. Although Mode 4 is approved for a broadcast surveillance application, requirements and standards for point-to-point data link communications are presently being developed. While the E-TDMA concept is aimed at data-only applications, SOFREAVIA proposes that E-TDMA can be adapted to provide voice as well.

The relevance to aeronautical communications is based on the fact that these systems were developed for aviation with air-ground and air-air communications as their primary purpose. Similarly, they were all conceived and developed to be implemented and transitioned within the existing AM(R)S VHF allocation. This attribute does differentiate them from the other systems studied in that additional radio frequency spectrum would not necessarily be required if any proved adequate in addressing the capacity increases and the anticipated future data rates. Because of their designed intent to serve aviation directly, this family serves well as a benchmark in assessing the technical performance of the other candidate systems, their infrastructure and avionics architectural and cost implications, airline equipage issues, as well as the risk and timeframe for airspace insertion. More importantly, in appreciation the investment-to-date in development and resulting maturity, it is important to investigate whether any can, and should, be used to provide a subset of required services for future aeronautical communications. The trade space of solutions consists of adaptation of commercial communications systems as well as combination solutions, where an existing system, aviation-specific or not, may be used with another newly implemented and adapted system to provide the composite of voice and data services.

The family of VHF Digital Link (VDL) services was developed through ICAO. As of 2004, three different candidate VDL systems for ATN subnetworks, Modes 2, 3, and 4, are included within the ICAO Standards and Recommended Practices (SARPS), Annex 10. They are all designed for 25 kHz channel spacing with the exception of Mode E (8.33 kHz). The evolution of the family is shown in figure 3.6-1.

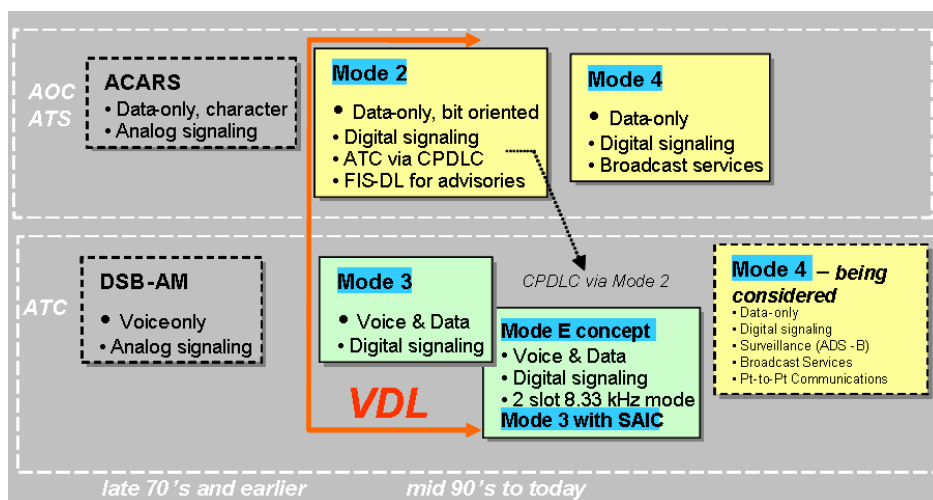


Figure 3.6-1: Family of VDL Service

3.6.1.1 *Mode 2*

The legacy of these digital VHF sub-networks for AOC, ATS, and ATC communications started in the early 1990s when the ARINC's Airborne Communications and Reporting System (ACARS) system was deemed inadequate for future AOC and ATS needs. The ACARS system was a clever means to adapt a channelization scheme aimed at analog voice communications for pilot-to-airlines traffic to a scheme capable of carrying digital data for text messaging. This system would off-load pilots and provide, in some cases, automatic delivery of aircraft information important for aircraft maintenance and flight services. The signaling method is based on amplitude modulation using minimum shift keying (MSK) at 2400 bps. When it became clear that additional throughput would be required to support more information, the Mode 2 system was proposed. Truly digital in its signaling with varying pulse lengths, the Mode 2 system is bit-oriented versus the character-oriented ACARS system. Consequently, the Mode 2 system, which is a data-only system, could be used to transmit weather maps or other graphical data to the cockpit or the ground. Mode 2 uses the carrier sense multiple access (CSMA) medium access control (MAC) protocol to permit nearly statistically equal access to the channel by all users, but, as such, permits collisions of data. It possesses mechanisms for some degree of robustness in delivery of messages. This was deemed satisfactory for AOC messages due to anticipated traffic loading but soon, other services such as ATS and limited ATC message sets were proposed, adding additional loading to the system. Mode 2 today, especially in key introductory sites in Europe, provides for CPDLC messaging as well as Flight Information Services—Data Link. Note that one channel at 136.975 MHz is currently approved for usage and frequency planning criteria from interference testing through EUROCONTROL⁸⁷ has shown that one guard channel is needed to step-wise deploy more Mode 2 channels. At the service level, Mode 2 does not implement priority levels for data queuing so it does not provide Quality of Service guarantees.

3.6.1.2 *Mode 3*

During the early 1990s, the FAA began development of an integrated voice and data system to carry dedicated Air Traffic Control communications in the U.S. The nature of safety-related ATC communications required a protocol more deterministic in delivery of service than that of Mode 2. At ICAO AMCP/5 in April, 1998, initiation of the formal validation process for the ICAO VHF Digital Link (VDL) Mode 3 SARPs was approved. System developers proposed a different medium access protocol, Time Division Multiple Access (TDMA), which dedicates certain time slots for groups of users. In fact, ground-to-air and air-to-ground traffic are carried in reserved frames within a media access cycle, and, as a result, the Time Division Duplexing (TDD) nature serves to duplex this traffic to avoid interference and data collisions. This scheme essentially guarantees that the air traffic controller has dedicated access in the channel through use of a management channel which carries control information to offer system features that highlight a real benefit of Mode 3—namely controller override, anti-blocking, next channel uplink, and urgent downlink. Mechanisms designed into the Mode 3 protocol, such as reserved slots for acknowledgements to notify the sender that a data burst was successfully received, in addition to use of priority levels in data framing, result in the integrity of data transmission necessary for ATC usage. For the FCS study, Mode 3 was evaluated for its innate voice and data capability within the same channel.

3.6.1.3 *Mode 4*

A data-only, broadcast system was developed in the late 1980s for a surveillance application for maritime harbor navigation and is also used for open ocean situational awareness for helicopters navigating near oil rigs. The system, termed Mode 4, was conceived and developed in Sweden as a method of deriving situational awareness of nearby cooperative platforms through frequent broadcasts of these platforms' positions. Through three dimensional location reporting expected to be derived through the Global Navigation Satellite System (GNSS), a platform could assimilate all platform's positions, velocities, and potentially, their intent. The system was designed for the VHF band of 25 kHz channel spacing but insertable within the 108 to 117.975 MHz navigation allocation with the requirement to not interfere with

the Instrument Landing System (ILS) Localizer function, and within the 118 to 137 MHz AM(R)S band as well. The ICAO SARPS (Annex 10 Volume 3, Part I) specifies 117.975 to 137 MHz for VDL Mode 4 for data link communications operations. Optional provisions are made for the 108 to 117.975 MHz band for broadcast operations. In fact, the World Radio Conference (WRC) 2003 (Geneva, June 2003) approved operation of VDL Mode 4 in the ARN band (112 to 117.975 MHz) for surveillance applications. Operation from 108 to 112 MHz is not authorized until compatibility with broadcast FM services is demonstrated.

The Mode 4 was adapted to aviation usage during the 1990s and the system employs a self-organizing TDMA MAC layer through use of a process where time slots, once requested by mobile (airborne) platforms based on a surveyed usage within the channel by the mobile terminal, are scheduled by a ground scheduler to provide nearly equal access to the channel. While SARPS standards for this subnetwork have been approved already for a surveillance application only for broadcast mode, standards are being developed presently for adaptation as a point-to-point data-only communications function. For the FCS study, Mode 4 was evaluated on the basis of providing a voice and data capability within the same channel through the same process Mode 2 was evaluated: by adding voice capability through a VoIP which would require modifications to the protocol. This, it was considered, was reasonable to make a fairer comparison of the Mode 4 capability within the family of VDL services.

3.6.1.4 Adaptations of Mode 3

A couple of enhancements to the Mode 3 system were also evaluated in the FCS study. Both provide voice and data in the same exact way as Mode 3 does—they are not actually new systems. One enhancement is that of the Mode E system, a two-time slot version of the Mode 3 protocol for insertion in 8.33 kHz channel spacings with a few additional features including increased address space. The second is use of Mode 3 with Single Antenna Interference Cancellation (SAIC) employed within the receiver, a digital signal processing augmentation for reception for enhanced frequency re-use performance, a capacity increasing parameter.

3.6.1.5 Mode E

The Mode E system⁸⁸ was conceived and prototyped by Rockwell-Collins in early 2000s using many of the protocol aspects of Mode 3 but with several differences. One is its reduced bandwidth and use of framing with two time slots for insertion into airspace divided into 8.33 kHz channel spacings. There are 6 channels for Mode E as compared to 1 channel for DBS-AM. The use of these parameters for a digital voice-only function offers a maximum voice channel capacity increase per channel converted, theoretically, of up to 6:1 if three of these 8.33 kHz channels replace a 25 kHz DSB-AM channel. If a single 8.33 kHz DSB-AM channel in Europe, for example, is being replaced with a single Mode E, 2 slot voice only channel, then the apparent capacity increase per channel converted is, at best, 2:1. This is still significant. The same vocoder approved for use in Mode 3 is used in the proposed Mode E system, so the same encoded vocoder bit rate of 4800 bps is employed. In addition to two voice slots, or circuits, Mode E allows for a configuration where one voice circuit and one data channel is allocated in the same 8.33 kHz TDMA channel where the data slot provides the user with a 4800 bps data rate. For the FCS study, Mode E was evaluated on the basis of providing a voice and data capability within the same channel but its usefulness as a voice capacity increasing system for a voice-only mode is also included.

3.6.1.6 Mode 3 with SAIC

SAIC is a multi-user detection estimation algorithm that is being applied to cellular telephony systems since it can add additional capacity to areas of coverage resulting from frequency reuse. SAIC is implemented as a semi-blind signal processing algorithm within the receiver and, conceptually, does not change anything within the normal Mode 3 analog hardware portion of the receiver design. The algorithm is blind with respect to the data of the interference but does depend on a priori knowledge of a discriminatory training sequence of the desired signal. The algorithm is suited for TDMA systems which

employ a discriminatory symbol sequence that may be used to separate user's transmissions at a receiver. The technique has been reported in published trade journal articles⁸⁹ to offer a separation ability of desired and undesired co-channel energy as close in RF power level as a few dB (5 dB may be more realistic). This is to be compared to the nominal 20 dB co-channel interference (CCI) RF power ratio which is driven by the modulation system employed, namely, 8PSK, and as reflected by MOPS requirements for Mode 3 receivers.

The true capacity gain afforded by this technique is difficult to estimate without employing an adequate capacity prediction model for airspace spectrum planning which requires a CCI performance parameter as an input. For the FCS study, the utility of Mode 3 with SAIC was evaluated similarly as Mode 3 and is not treated separately in the text of this report. Enhancements due to SAIC for channel capacity are not readily quantifiable in category 1B1 in the evaluations and are considered as not offering a significant increase in terminal domains since its capacity gains would be only useful in enroute phases where CCI is typically encountered. Mode 3 with SAIC in enroute domains would likely result in easier spectrum planning if advertised CCI performance of ~5 dB is realistic.

3.6.1.7 E-TDMA

SOFREAVIA briefed the E-TDMA concept to RTCA Special Committee SC178 in April 1998. SOFREAVIA stated that, at the time, Mode 3 and Mode 4 were envisioned to be inadequate in providing a general purpose data link for aviation. They proposed the E-TDMA system with the assumption that no requirement existed for an integrated voice and data system. A second generation system could not only provide the strengths of these other VDL systems but additional features as well. This concept is based on a cellular architecture of ground systems. Yet a ground station is not absolutely required in some instances. A primary focus on the concept is that of providing a managed Quality-of-Service (QoS) throughout the service volumes.

Some design drivers were discussed in this briefing which highlight goals for its end system. First, a sustainable migration path is needed that provides insertion into the existing VHF AMRS band. Individual, narrowband E-TDMA channels could be inserted anywhere within the 117.975 to 137 MHz band. Second, avionics cost must be held low. Third, safety certification is addressed through traceable QoS specifications and common mode failures with other CNS systems is to be avoided. Fourth, different services will be provided including broadcast, addressed air-to-air and air-ground. Finally, differing densities of ground stations must be accommodated in the traditional sense of today's cellular telephony ground architectures.

The accommodation of the different service types for surveillance, for AOC, for ATC, etc. will be accomplished, according to SOFREAVIA, through a flexible slotting scheme providing reserved time slots for broadcast functions from the ground stations or from aircraft mobiles broadcasting their ADS-B position reports and other flexibly allocated time slots for the various functions. The use of deterministic slot scheduling and assignments is a key enabler to providing higher levels of QoS.

3.6.2 Selection of Evaluation Candidates via Minimum Threshold Test

All of the VHF subnetwork systems, i.e., Mode 2, Mode 3, Mode 3 with SAIC, Mode E (conceptual), Mode 4, and E-TDMA, were evaluated since they met the basic minimum threshold requirements during technology pre-screening. Where no voice mode is provided for Mode 2, Mode 4, and E-TDMA, a Voice-over-Internet Protocol (VoIP) mode was assumed to provide the voice capability. And, while an IP over Mode 2 concept was proposed, this evaluation focused on a means to implement a voice capability (through VoIP) using the Mode 2 system to effect a voice and data system. This increased the candidate baseline of digital narrowband services and permitted a fairer comparative analysis. This was deemed acceptable since Mode 2, Mode 4, and E-TDMA are packet mode services and, it was judged, could be modified to provide a packet-based VoIP voice capability with potentially reasonable protocol additions.

Table 3.6-1: Rationale for Selection of Custom Narrowband Candidate Solutions

System	Evaluate	Rationale
Narrowband		
VDL 2	Yes	This system has been standardized by ICAO and is in use
VDL 3	Yes	This system has been standardized by ICAO and was developed specifically for providing ATC communications in the VHF band.
VDL 3 SAIC	Yes	SAIC offers promising utility for VDL 3. By decreasing the frequency reuse distance, the capacity offered by VDL3 should be substantially increased. While this was analyzed, this truly is not a separate technology, but an optional enhancement for VDL 3 and VDL E
VDL E	Yes	This technology is a modification of VDL 3. As such, standards development is leveraged, and technical maturity is relatively high. This technology has the additional advantage of (seemingly) being able to transition in 8.33 kHz airspace.
VDL 4	Yes	This system has been standardized by ICAO.
E-TDMA	Yes	This system is an alternative to VDL 4 with some similar features

3.6.3 Technology Description

3.6.3.1 Services Provided and Key Features

This narrowband VHF family of services, that, in their present configuration, is composed of data-only services (Mode 2 Mode 4, and E-TDMA) and one which provides both voice and data, namely Mode 3 (and Mode 3 with SAIC) and its similar companion, Mode E (conceptual). These services were each designed for aviation needs and, as a result, provide an array of connection-oriented and connection-less services. Of the families of commercial or military systems studied under this portion of FCS, these VHF sub-networks provide the most aviation-specific service protocols since they were specifically designed or utilized for aviation services. The different applications of each warrant the level of service that the protocol stack was designed to provide, which directly affects the Quality of Service level attainable from them. As an example, Mode 3 was designed for Air Traffic Control, and, consequently, provides framing based on priority and also reserves time slots for acknowledgements to received data bursts. Time slots for voice are reserved, in addition, since ATC voice must have low latency and service-on-demand. These examples of protocol mechanisms to provide data integrity consume, in effect, available bandwidth, but provide the level of service demanded for ATC for the case of Mode 3. Each of the modes will be examined for their individual services and key features but first a general discussion is provided regarding the Aeronautical Telecommunications Network (ATN) architecture requirements that these sub-networks must accommodate.

3.6.3.1.1 Mobility

The services provided by these sub-networks must support a level of mobility, sometimes called roaming in the cellular mobile subscriber world, such that aircraft using a Mode 2 service application, for example, maintain connections at the ATN level. This means that ground-to-ground routers must pass and/or update routing path information, e.g. router address tables, between ATN ground elements in order for connections to be maintained as the aircraft passes between sectors (Mode 3, e.g.) or between service provider coverage areas (Mode 2). These make-before-break connections between old and new service volumes can be transparent to the pilot, but, sometimes, is not. At a high level, the connectivity must be maintained at the session layer to ensure that this connectivity, at the application level is seamless. These VHF sub-networks were designed to ATN mobility requirements and, as a result, employ mobility management functions. Some ATN mobility requirements, at a high level, are discussed next.

The ATN must support roaming between networks or domains via intra and inter-domain routing protocols. Aircraft may simultaneously attach to more than one subnetwork. Routers keep a route map for each aircraft which is passed between ground routers and ATN size is, in part, limited by the router table capacity. The ground-to-ground infrastructure should be able to report join and leave events as well as aircraft identification. These are some details that must operate for the applications in aircraft to operate

seamlessly over large coverage volumes. The services provided by these mobility-enabled VHF sub-networks are summarized next.

3.6.3.1.2 *Mode 2*

Mode 2 provides only non-time critical AOC messaging and this service is provided by only a couple of large commercial service providers in the world, namely ARINC and SITA. Mode 2 has rather recently begun carrying limited non-time critical Air Traffic Services messaging including pre-departure clearances, among others. It has also been used, albeit in a limited fashion, to provide the data link for an ATC application, such as Controller-to-Pilot Data Link (CPDLC). The backbone of Mode 2 services reside in its Data Link Sublayer (DLS) which is based on the use of Aviation VHF Link Control (AVLC), which is derived from the standard High Level Data Link Control (HDLC) protocol. This Layer 2 portion of the protocol stack provides a connection-less broadcast function as well as a connection-oriented capability for point-to-point data. At the subnetwork layer, a connection-oriented ISO 8208 Subnetwork Access Protocol (SnAP) is used. Note that priority support is not provided so that some ATC-critical messages or applications cannot be transported through this service. Since the service is provided over a portion of VHF spectrum reserved for AM(R)S use, the favorable propagation performance of the VHF signal results in coverage areas of about 200 nm. This is similar to voice coverage over DSB-AM today.

Note that Mode 2 was developed for a-periodic traffic where the entire message is available before transmission of individual packets begins. This works well in a certain traffic densities but does not fare well in higher density traffic when the channel loading increases significantly.

3.6.3.1.3 *Mode 3*

Mode 3, including the concept of Mode 3 with SAIC, provides an integrated party-line voice and data capability. Features for voice services are shown in the table 3.6-2 below. The features are facilitated by use of a Management channel, a separate burst from the voice or data burst but usually contained in the same MAC frame.

Table 3.6-2: Mode 3 Standard and Enhanced Voice Features.

Feature	Notes
Pre-emption	Controller has priority and may over-ride stuck microphone
Step-on protection	Use of voice status bits in M burst controls PTT access
Urgent downlink	Pilot may notify controller "off-line" automatically that he desires use of channel
Next Channel Uplink	Ground station can automatically notify airborne unit of next sector's frequency and user group information

Mode 3 was designed for ATC voice and data messages and the critical nature of ATC usage, in some cases, requires use of additional latency and integrity mechanisms to achieve reliable and available data link performance designed into Mode 3. For example, Mode 3 was based on an acknowledged, connection-less data link services (A-CLDL) layer where acknowledgements are placed in reserved time slots. As with Mode 2, Mode 3 provides a connection-less broadcast feature. At the subnetwork layer, it uses either a connection-oriented ISO 8208 protocol or a connection-less network protocol (CLNP). It also provides a reservation-based ground-air data link with 4 level, grouped priority. The use of priority grouping and transmission of priority frames and use of reserved timeslots for acknowledgements contributes to the integrity of the data link. The use of dedicated timeslots for voice with the added features of controller override, next channel uplink automation, among others adds to the availability of the safety-critical voice function for ATC. Mode 3 was designed to operate within the aeronautical VHF band of 118 to 137 MHz and, as a result, has a communication range of about 200 nm although guard times designed into the protocol for three slot modes can offer extended range where propagation conditions and transmit power will permit.

Then services for Mode 3 are distinguished by the configuration mode of the ground station. These configurations are classified according to the mix of voice and data services provided as well as the

number of user groups supported. User groups may be assigned to groups of aircraft based on a particular sector of airspace and, consequently, get a reserved timeslot or timeslots for either or both of voice and data. Four timeslots define a frame but three are used for long range coverage areas where extra guard time is used to allow for larger propagation times. As an example, a 4V (voice) configuration will support four voice circuits (timeslots) labeled A, B, C, and D. Timeslot A would be used by all aircraft in an area of airspace, most likely a single sector, and the other three slots would be assigned similarly. It is in this manner that a single 25 kHz channel that, today supports one user group, may be split into a total of four groups. With the advent of voice encoding technology and bandwidth efficient modulation schemes, the inefficiency of today's use of double sideband amplitude modulation (DSB-AM) in the present VHF AMRS allocation becomes clearer.

When data services are desired, a mixed mode may be configured. For example, a 2V2D mode can support two user groups with each user group possessing a voice slot as well as an associated 4800 bps data timeslot. Other mixed modes include 1V3D, 3V1D, 2V1D and 3T. The 2V1D mode permits two voice circuits and 1 shared data channel. The 3T mode provides, in effect, one large user group with 3 data timeslots and 1 shared voice circuit. This is useful where the traffic is essentially data. The main user group is further logically divided into three separate user groups (timeslots B, C, and D) for traffic and timeslot A carries the management channel information for all three user groups. Addressing bit field restrictions limit the number of aircraft per each of the three groups to 60 aircraft for a total within the main user group to 180 aircraft. Figure 3.6-2 shows the Voice and Data composition of the framing structures for normal and extended range modes for various Mode 3 configurations.

An example illustrating the flexibility of these configurations and modes is the use of wide area coverage configurations. These are typically three slot (extra guard band used in the timeslot) configurations designed to allow for coverage of large volumes of airspace by 3 ground stations. The 3V, 1V2D, 2V1D, 3T, 3S, and 2S1X modes are examples of this, where the latter two are used in diversity ground sites. Other configurations exist including 1V3D and 3V1D, and only the major configurations have been briefly discussed here.

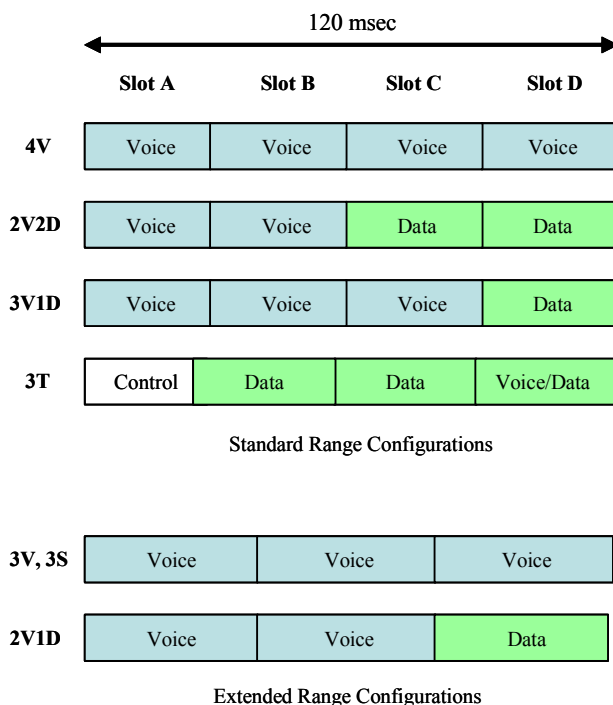


Figure 3.6-2: Mode 3 Timeslot Structures for Some Major Configurations

3.6.3.1.4 *Mode E*

The services for Mode E were conceived to offer the general voice and data services of Mode 3. Due to its reduced number of timeslots, the number of user groups, if differentiated by time slot assignment, is now a maximum of two. The services may be configured as 2V for two independent voice circuits or as a 1V1D mode where the first time slot is used for voice and the second for a 4800 bps data channel. A diversity mode called 2S is also available where both timeslots carry the same information as a sort of simulcast to aid in sectors which have blockage of signal coverage.

3.6.3.1.5 *Mode 4*

As far as aviation is concerned, Mode 4 is presently specified for a broadcast function for surveillance by the aircraft.⁹⁰ This surveillance capability is called Automatic Dependent Surveillance—Broadcast (ADS-B). Standards are presently in development for its usage for point-to-point data link communications for aviation. Consequently, it will provide an addressed service. A major focus for these standards is compliance with ATN requirements. The data link is advertised to achieve its data integrity level through a ground scheduling algorithm where requests for future timeslots by the aircraft are based on the aircraft's "sense" of the other network participant's transmitted requests. Collisions and contention for access can, in theory, be greatly reduced.

The scheduling process, in general, is facilitated by each aircraft calculating the ranges from their Mode 4 radio terminals to others in proximity. This is done typically by the broadcasting of the aircraft's position as determined by the sending aircraft's on-board GPS system. Knowledge of these distance-induced propagation time delays enables the efficient scheduling and usage of timeslots. In addition, if there is no ground station present, the aircraft Mode 4 terminals can also form a type of ad-hoc network by intelligently scheduling their timeslots. This mode may work in an enroute area since the accuracy which results from self-determination of other aircraft positions is less accurate than that resulting from a GNSS system such as GPS. In fact, timeslots may be reused if they belong to aircraft beyond the threshold distance, where received signal strengths are sufficiently low.

Mode 4 is required to provide a 15 level priority queuing for its DLS layer to give priority of transmission to higher priority application messages, or higher priority frames within a single application. In fact, these levels are not grouped as they are for Mode 3, so they are more capable theoretically. Mode 4 is also connection-oriented and can maintain multiple connections⁹¹ with different stations.

Mode 4 requires the use of Global Signaling Channels and, possibly, Regional Signaling Channels. These are dedicated channels which must be monitored by airborne radios in order to become aware of local configuration parameters, Service Discovery functions, among others. This monitoring requirement incurs the need for extra receiver(s) in the airborne avionics as well as separate frequencies and transmitters at ground stations. This is a distinct difference from that of Modes 2, 3, and E.

3.6.3.1.6 *E-TDMA*

The E-TDMA concept is intended to provide a data-only service with significant requirements for QoS. SOFREAVIA claims that the flexible slot structure may be adapted to provide a voice capability. In this sense, a VoIP addition discussed earlier appears to be a natural extension of the protocol to achieve a voice capability. The E-TDMA system also shares some characteristics as the other VDL systems. For example, the frame length is dependent on ADS-B reporting requirements and is estimated to range between 2 and 10 seconds. Another example is the use of Global Signaling Channels (GSC) like that employed with Mode 4. These channels are proposed to maintain QoS levels during intervals of network degradation. Such is the case for the warm and cold start features when a ground station, or stations, go off-line for any of several reasons. GSC's would serve to broadcast new ground station frequencies to alert aircraft mobiles the new channels to which to tune. They would also request a roll-call of mobiles (termed Hello mini-slots) to update the registry of aircraft within the newly established on-line ground

network. This feature implies requirements for aircraft and ground monitoring of service quality parameters. This type of QoS monitoring can be performed through counting slot collisions (indicating a synchronization or timing failure), mobiles sending reports of ground station outages notifying other mobiles, among others. A multi-level QoS system is proposed to permit ATN routers the connectivity to establish Switched Virtual Circuits according to the QoS level required.

An ISO 8208 subnetwork interface is proposed for connection to the ATN. This interface is coupled tightly with QoS maintenance.

For the air-to-air surveillance functions such as ASAS and ADS-B, two additional receivers are required in the avionics. While the primary receiver is used for the current cell the aircraft is located within, the additional receivers are tuned to downstream, adjacent cells.

The E-TDMA concept is based on several fundamental performance requirements. These include:

- 1) A high integrity MAC sublayer employing Statistical Self-Synchronization (S^3) and deterministic slot scheduling.
- 2) Contributions to data integrity and certification goals through careful, fast, error detection and correction mechanisms.
- 3) A master timing reference is not needed for both ground and the airborne radios—only a quartz clock need be used to provide the required short term accuracy. UTC accuracy need only be on the order of 1 second.
- 4) For ranging functions, fairly imprecise positioning performance may be adequate.
- 5) High throughput using low overhead for headers, FEC, and transmitter ramping.
- 6) Use of modular error correction where a minimal number of different codes and/or lengths are used for headers, and for short and long slot data

3.6.3.2 Functional Architecture

The functional architecture for the VDL family is similar in many ways. The generic architecture is shown in figure 3.6-3 for an ATC implementation. Note that AOC and ATS architectures may be slightly different in that the ATN Air-Ground Router may not be located at the remote site and that existing ACARS message processors are also located at the AOC service provider's remote site.

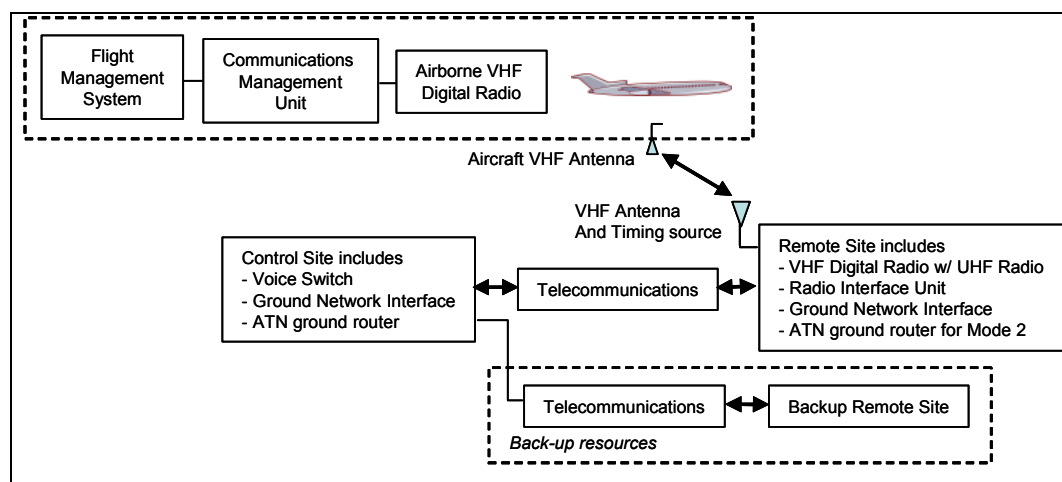


Figure 3.6-3: Generic Architecture for VDL System for ATC

3.6.3.3 *Air Interface Description: PHY, MAC, and Network*

A brief discussion of the air interfaces is provided next. The VHF family of custom, narrowband waveforms including Modes 2, 3, and 4 all are designed for 25 kHz channel spacings but Mode E is designed for 8.33 kHz spacings. The individual interface information is given separately for this family of waveforms and is specified in corresponding sections in the Standards and Recommended Practices (SARPS) for Modes 2, 3, and 4 and additional detail is provided for Mode 2 and Mode 3 in the Minimum Aviation System Performance Standards (MASPS)⁹² document.

Some commonalities for these modes exist and more detail may be found in the SARPS. The common areas in their respective protocol stacks are: A VDL Management Entity (VME) is used and is responsible for connection establishment and handoffs. The VME creates a Link Management Entity (LME) for each connection. Note that each subnetwork may handle more than one connection at any one time but may pass data to any one of these through one connection. The Data Link Sublayer (DLS) manages data communications between aircraft and ground stations, providing the addressing and controlling link usage. It maintains a Data Link Entity (DLE) for each connection, and manages a prioritized queue shared by every DLE. The Medium Access Control (MAC) layer is responsible for determining when to transmit a packet using the link. The distinct difference between Modes 2, 3, E, and 4 is the use by Mode 4 of a VDL Mode 4 Specific Services (VSS)⁹³ sublayer along with the MAC.

Some differences exist as well in the physical layer performance. Each has its own bit error rate that provides acceptable performance depending on the service type: voice or data. The VHF propagation medium works fairly well for narrowband waveforms considering the Doppler and delay spread behaviors. The link budget for D8PSK signaling does incorporate the relatively high E_s/N_0 (energy per symbol-to-noise density) ratio required for acceptable bit error rate. The use of D8PSK for Modes 2 and 3 requires a Signal-to-Noise ratio (SNR) at the detector input of approximately 16 dB⁹⁴. For Mode E, the required SNR is reduced by 3 dB due to the reduction in bit rate and, consequently, the necessary pre-detection bandwidth. This value results from the MASPS link budget input for energy per symbol-to-noise density ratio of 17.8 dB⁹⁵ for D8PSK. The SNR ratio results from the following calculation:

$$\text{SNR (dB)} = 10 * \log_{10}(E_s/N_0 * R_s/BW), \text{ where}$$

E_s = energy per symbol in Joules per symbol
 N_0 = Noise energy density in Watts per Hz
 R = Symbol rate in symbols per second
 BW = Pre-detection bandwidth in Hz

The benefit of this E_s/N_0 value is the increase in bandwidth efficiency, i.e. bandwidth utilization factor. Mode 4, on the other hand, while it requires a lower minimum E_s/N_0 ratio, does not achieve as high a bandwidth utilization factor, but its link budget may numerically show that it supports slightly longer ranges, everything else being equal.

3.6.3.3.1 *Mode 2*

The Mode 2 lower layers consist of the PHYSICAL Layer and the Link Layer. The Link layer is further divided into the MAC sublayer and the Data Link Services (DLS) sublayer.

PHYS and MAC Layer

The physical layer employs eight phase shift-keyed (8PSK) modulation with differential encoding, termed D8PSK. The burst rate is 31.5 kbps, or equivalently, 10.5 ksymbols/sec. The parameter which describes the roll-off factor for the baseband pulse shaping filter, alpha, is 0.6. The advantage of this value of alpha is the bandwidth reduction that results, but the penalty is the peak-to-average power ratio of about 3.4 dB in the envelope of the radio frequency signal to be amplified. This higher ratio makes it more difficult to

contain or limit the adjacent channel energy in the transmitted spectrum, an effect that directly impacts the capacity of deployment due to number of guard bands in frequency assignments. It also can increase the level of interference on other nearby channels, especially for cosite scenarios onboard aircraft and also air-to-air scenarios. Minimum Operational Performance (MOPS) specifications for adjacent channel power from the transmitter probably require some form of transmitter linearization circuitry that prevents energy in these nearby channels from exceeding specified levels. The need for spectrum management and adjacent channel power containment in avionics is even more important since Reduced Vertical and Horizontal Separation standards are being implemented or being considered. Another parameter that affects channel capacity or efficiency of spectrum usage is that of co-channel interference (CCI) power ratio and, for D8PSK, it is roughly 20 dB.

The MAC sublayer implements a non-adaptive, p-persistent Carrier Sense Multiple Access (CSMA) algorithm to equitably allow all stations the opportunity to transmit. The bursts may vary in length based on the number of payload bits to be transmitted, but the typical maximum transmission interval is expected to be about 500 msec while the maximum packet size is around 2048 octets. The half second upper limit results from a quick calculation: 2048 bytes x 8 bits/byte /31.5e3 bps. The MAC sublayer is a listen-before-transmit concept based on the Aloha protocol with collision detection and avoidance. The use of randomization in timer parameters in the MAC sublayer is a key to providing efficient and nearly equal access to the channel.

DLS

Reliable connection-oriented point-to-point data services are provided using a connection-oriented DLS sublayer. The DLS sublayer also provides an unacknowledged, connection-less, broadcast service. The DLS supports bit-oriented simplex air/ground communications using AVLC (mentioned earlier). The DLS performs frame sequencing, error detection and frame formatting, including that for the AVLC protocol.

The Mode 2 payload data is protected via Forward Error Correction through use of a Reed Solomon (255,249) 2^8 -ary FEC code. Error detection is provided through Cyclic Redundancy Check. Header information is protected via a (25,20) block code.

Network Layer

As mentioned earlier, the Mode 2 subnetwork layer is connection-oriented and uses the ISO 8208 Subnetwork Access Protocol (SnAP). A connection-less network protocol (CLNP) is used at the network layer and serves as the interface to the Inter-Domain Routing Protocol (IDRP) for access to other ATN elements. The full protocol stack for Mode 2, from ground through avionics as well as the subnetwork attachment and demarcation, is shown in figure 3.6-4.

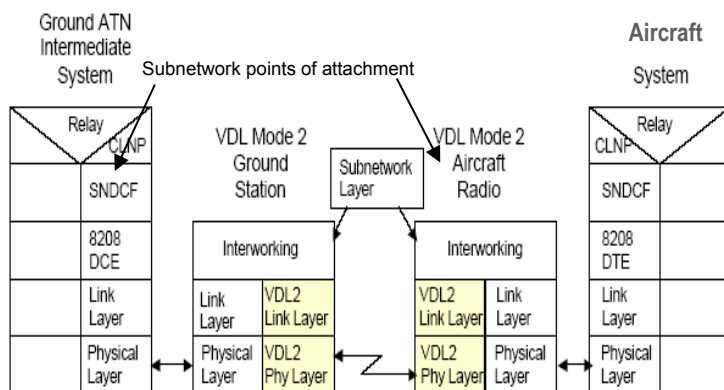


Figure 3.6-4: Mode 2 Ground and Avionics Protocol Stacks.

3.6.3.3.2 *Mode 3 and Mode E*

The lower layers of Mode E will be included in the following discussion since it is derived from the Mode 3 system. The lower layers consist of the PHYSICAL Layer and the Link Layer. The Link layer is further divided into the MAC sublayer and the Data Link Services (DLS) sublayer.

PHYS and MAC Layer

Similar to Mode 2, the physical layer for Mode 3 and Mode E uses eight phase shift-keyed (8PSK) modulation with differential encoding, termed D8PSK. The burst rate for Mode 3 is 31.5 kbps, or equivalently, 10.5 ksymbols/sec and for Mode E, the burst rate is half this, or 15.75 kbps. The parameter which describes the roll-off factor for the baseband pulse shaping filter, alpha, is 0.6 for Mode 3 (same as Mode 2). For Mode E, it is 0.3 to facilitate the narrower bandwidth and channel spacing compared to Mode 3. The advantage of lowering the value of the excess bandwidth factor (alpha) is the bandwidth narrowing, but the penalty is an increase in the peak-to-average power ratio (relative to Mode 3) in the envelope of the radio frequency signal to be amplified. Additionally, while a decrease in alpha theoretically concentrates the modulation energy more compactly in bandwidth, the undesirable increase in adjacent channel power due to the introduced amplitude and phase distortion caused by real power amplifiers is an inherent tradeoff in utilizing bandwidth limiting, baseband pulse shaping filters. Power amplifier designers trade DC power efficiency for linearity of the transmitted waveform for signals possessing a non-constant envelope. However, technology is available to prevent the energy from exceeding MOPS-specified levels and this technology has already been successfully implemented in pre-production Mode 3 avionics, albeit at some cost to avionics but potentially retaining some power efficiency. The need for spectrum management and adjacent channel power containment in avionics is even more important since Reduced Vertical and Horizontal Separation standards are being implemented or being considered.

One distinct advantage of Mode E, owing to its reduced bandwidth, is better receiver sensitivity by 3 dB compared to Mode 3. In free space, this would provide an additional 30% communications range. This may also be thought of as 3 dB additional link margin or, equivalently, would permit a reduction in transmitter power by half for the original range.

For Mode 3, timeslots for normal, standard range (~ 200 nm range) operation are 30 msec long and a frame for the time division-duplexing (TDD) of Mode 3 is 120 msec long. One MAC cycle is 240 msec long. As result, four timeslots constitute a frame with each slot permitting guard time for a 200 nm range. In extended range mode, only 3 slots are used and each slot is 40 msec long, providing guard time for more than 300 nm. A 6 second epoch derived from the 1 pps timing reference used to align certain functions is composed of 25 MAC cycles. Note that an external timing reference is required for the ground system and is expected to be supplied from a GNSS receiver set. For Mode E, the timeslot length is 60 msec and its guard time allowance permits more than 350 nm propagation distance.

A MAC timeslot usually, but not always, contains two different types of bursts. The control function is provided through use of a Management channel, or M-burst. The payload information is contained within the V/D burst. Both have special synchronization sequences that signal to the receiver what type of burst to expect. And both types of bursts contain header and/or system data. In general, most slots structures contain a Management burst followed by a Voice or Data (V/D) Burst. The 3T (trunked) configuration, for example, does not follow this exact structure. Another type of burst called a Handoff Burst facilitates handoffs as sectors are transitioned by the aircraft. The general structure of the various non-3T configurations is shown in figure 3.6-5. For Mode E, the timeslot uses both a Management burst followed by a Voice or Data Burst. The structure of a 3 and 4 slot structures containing a Management and V/D burst is shown in figure 3.6-5.

For voice operation, Mode 3 supports simplex voice operation with preemptive access for authorized ground users. For data operation, the MAC sublayer implements a ground station centralized, reservation-based access to the channel which permits priority access.

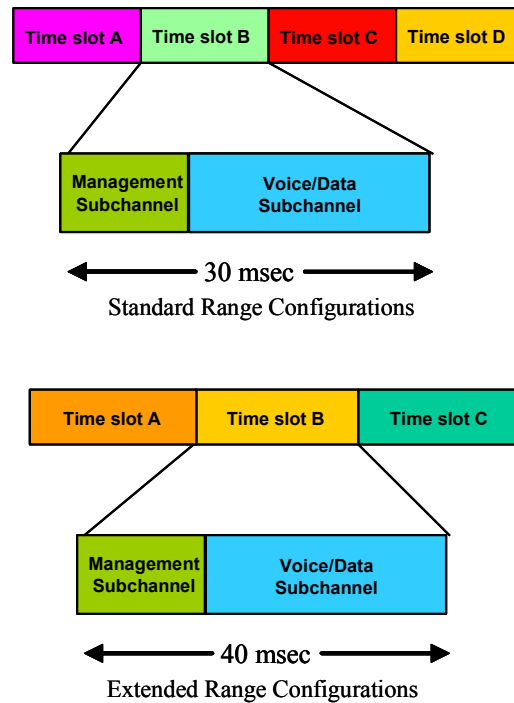


Figure 3.6-5: Use of M and V/D Bursts in 3 and 4 Slot Arrangements for Mode 3.

DLS

The Mode 3 DLS provides an acknowledged connection-less point-to-point data link services as well as a connection-less broadcast service. Acknowledgements are partially handled by the MAC layer to minimize latency. The DLS provides error detection and recovery, and aircraft station address identification. It is often that some vendors may opt to perform frame sequencing in the MAC sublayer. Data frames are transferred in the information fields of information (INFO) and control (CTRL) frames. Only one subnetwork packet at most can be contained in an INFO frame.

The Mode 3 576 bits of payload data are protected via Forward Error Correction through use of a Reed Solomon (72,62) 2^8 -ary FEC code. Error detection is provided through Cyclic Redundancy Check. Note that voice is transmitted without FEC beyond the vocoder's algorithmic FEC protection. Header information is protected via (24,12) Golay code. Bit scrambling is also employed.

Network Layer

The Mode 3 subnetwork layer may be either connection-oriented using the ISO 8208 Subnetwork Access Protocol (SnAP) or connection-less using a CLNP protocol. A connection-less network protocol (CLNP) is used at the network layer and serves as the interface to the Inter-Domain Routing Protocol (IDRP) for access to other ATN elements.

The protocol stack for the ground and airborne portions of the Mode 3 system with an 8208 connection-oriented subnetwork attachment are shown in figure 3.6-6.

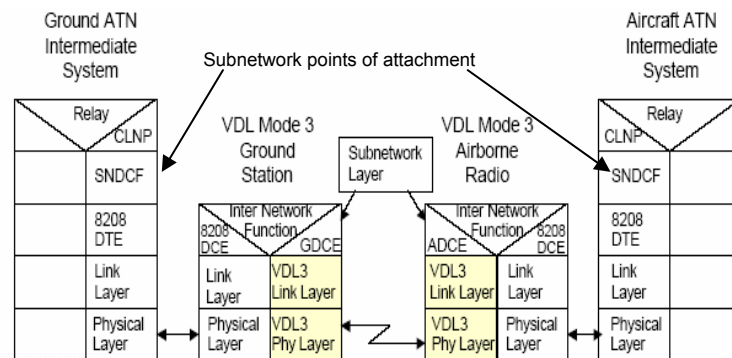


Figure 3.6-6: Mode 3 Ground and Avionics Protocol Stacks.

Mode 4

PHYS and MAC Layer

While much of the PHYS layer for Modes 2, 3, and E are similar, the physical layer for Mode 4 is different. Mode 4 uses Gaussian Frequency Shift Keying (GFSK) modulation. The burst rate is 19.2 kbps and, since this modulation is 1 bit/symbol, the symbol rate is identically 19.2 ksymbols/s. The advantage of GFSK is a lower peak-to-average power ratio. Power amplifiers can be designed to efficiently amplify this type of waveform while minimizing adjacent channel (unwanted) energy. The penalty is a reduction in bandwidth efficiency of nearly 1 bit/sec/Hz. Another benefit of GFSK is the improved CCI performance of a required 12 dB. This fares better than that for D8PSK used by the other VDL modes.

Timeslots are based on the short transmission protocol of a minimum duration of 13.3 msec. There are 4500 timeslots per superframe and the rate of superframes is one per minute. Figure 3.6-7 shows the concept of how superframes are divided into the various types of timeslots. Multiple access protocols may be used for scheduling purposes—Reserved Access (Periodic Broadcast and Unicast), Random Access, Fixed Access (Ground Quarantine). Furthermore, reserved slots can be re-used by aircraft if the received power levels satisfy co-channel interference ratio requirements. A VHF digital link (VDL) Mode 4 burst is composed of a sequence of source address, burst ID, information, slot reservation and frame check sequence (FCS) fields, bracketed by opening and closing flag sequences. Acknowledgements for this protocol are handled by explicit reservations within the information bursts to the receiving station. The long transmission protocol permits packet transmissions of integer multiples of this duration. The maximum number of bits in a long burst can, in theory, be very large, but, in practice, the efficiency of the data link will suffer. Acknowledgements for the long protocol are transmitted along with a receive ready message which indicates a request reservation to the sending terminal for new information.

Note that an external timing reference is required for the ground system and is expected to be supplied from a GNSS receiver set.

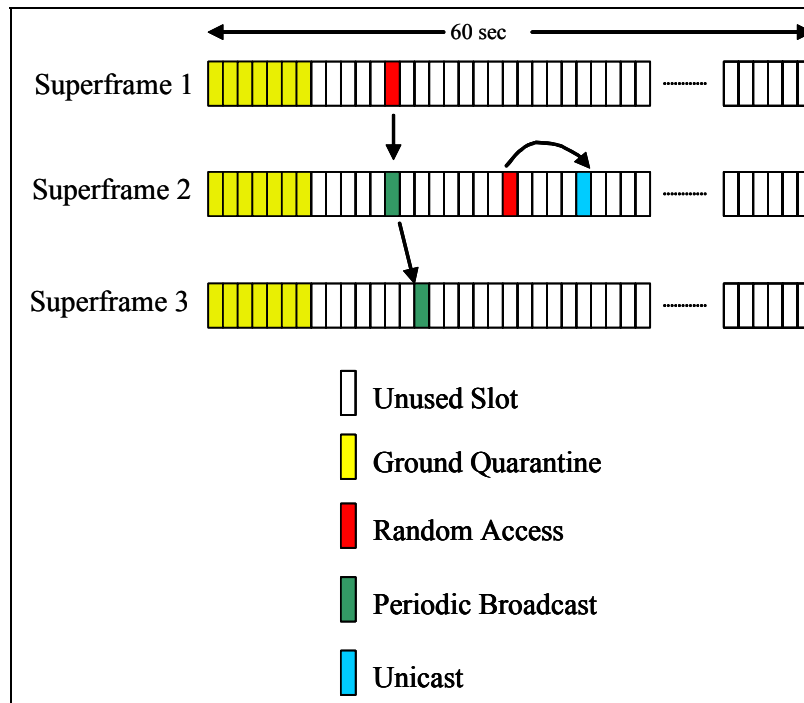


Figure 3.6-7: Mode 4 Concept of Timeslot Scheduling.

DLS

The Data Link Sublayer (DLS) provides a point-to-point protocol supporting both ground/air and air/air exchanges. For ground/air exchanges, connection management is handled by the LME, using a negotiated setup connection-orientated protocol (NSCOP). For air/air exchanges, the DLS defines a ZOCOP protocol with link establishment and disestablishment controlled by timers, allowing rapid link negotiation between aircraft.

The Mode 4 DLS is a simple information exchange protocol which provides explicit acknowledgement of each data packet and provides mechanisms to provide data transfer in reserved slots avoiding loss rates and delays associated with random access. This includes the ability to link sequences of DATA packets, providing continuous transfer in reserved slots. The DLS performs packet fragmentation to allow long user data packets to be transferred across the link in fragments optimally matched to the link conditions. It detects duplicate transmissions and suppresses processing of these packets via a simple toggle bit mechanism. The use of segmentation and flexible packet lengths adds to efficiency of sharing the channel among high and low bandwidth users. The DLS provides support for the 15 priority levels defined for the ATN. Acknowledgements to received packets are also scheduled within reserved timeslots. As a result, Quality of Service for delivery of services may be provided.

A typical sequence of messaging for a data packet using the long transmission protocol⁹⁶ involves an RTS burst, an RR.1 burst, an INFO.1 burst, an ACK.1 followed by an RR.2 burst, a request for more INFO slots, and, finally, the ACK burst for the last INFO burst.

As an example of a Mode 4 data transfer, the bursts for the long transmission protocol are described next.

- **RTS burst:** The Request-to-Send burst uses the Random Access method of scheduling.
- **RR.1 burst:** The Receive-Ready burst is an information transfer request that instructs station 1 to send INFO burst number 1. This burst also includes an information transfer reservation.

- **INFO.1 burst:** Contains the first part of the message (useful data). This burst does not include a reservation.
- **ACK.1 and RR.2 burst:** This single slot burst acknowledges the INFO.1 burst and makes a new information transfer request reservation for the next INFO burst.
- **Last ACK burst:** (ACK.n) After the last INFO burst has been received, a burst is returned to station 1, confirming that the last INFO burst was successfully received.

E-TDMA

PHYS and MAC

The E-TDMA physical layer, as with Modes 2, 3 and E, employs D8PSK modulation. The clock for an airborne radio must not drift more than 50 usec. The system is expected to operate over a Physical Bit Error Rate of $1\text{E-}3$ and a required Residual Message Error Rate of $1\text{E-}7$. The Media Access cycle is based on frames that may range from 2 to 10 seconds. The frame interval is dependent on local requirements and, primarily, on any ADS-B broadcasting update rates. The frames are repeated as in figure 3.6-8.

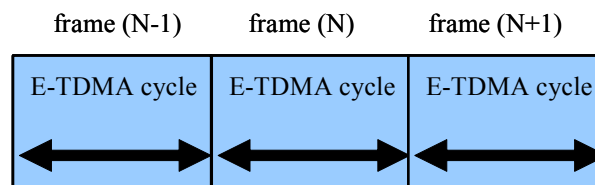


Figure 3.6-8: *E-TDMA Slot Structure*

The frames are composed of time slots that consist of propagation guard time, transmitter ramp up, synchronization interval, the data burst, the CRC code bits, and the transmitter ramp down interval. This slot structure is depicted in figure 3.6-9.

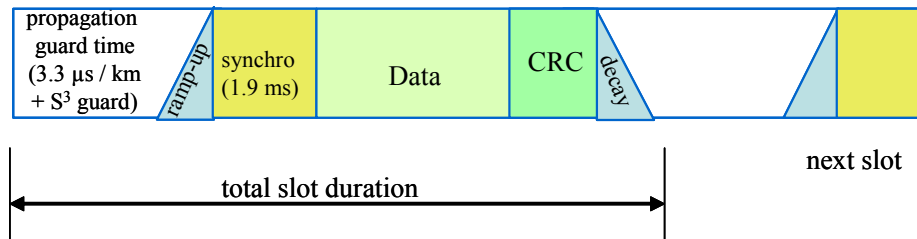


Figure 3.6-9: *E-TDMA Slot Structure*

The slots are allocated based on QoS requirements, and may be based on application or functionally grouped. Figure 3.6-10 shows this concept.

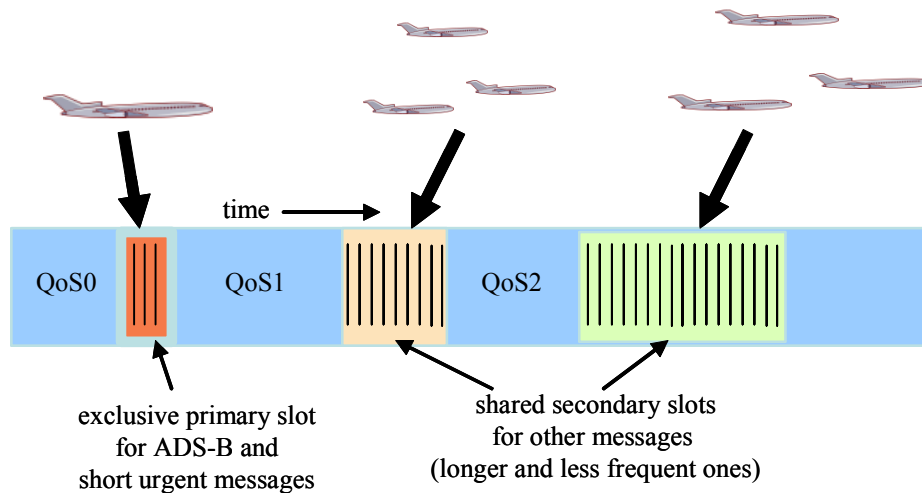


Figure 3.6-10: Allocation of E-TDMA Slots based on QoS and Function

In figure 3.6-10, the QoS levels indicate service delivery guarantee levels. For highest level, for example, a dedicated time slot(s) is reserved, and transit times and minimum throughput rates are guaranteed. The use of deterministic slot assignments is important for QoS performance. For lower level QoS time slots, the time guarantees are lesser since these slots are shared among many aircraft, potentially, and time guarantees are measured statistically.

As an example of functional grouping, all uplink time slots may be grouped at the beginning of the frame and, in a case like this, QoS demarcation boundaries are virtual throughout the frame. For grouping of ground beacon and information bursts like this, an intermediary beacon for synchronization may be needed midway within the frame if airborne radio clocks are not sufficiently stable for this length of time.

Time slot reservations are provided for within the primary time slot allocation where QoS level is highest. A reservation flag is set here by the requesting aircraft and notice is implicitly provided to all members of the channel that future timeslots are requested by that aircraft. A reservation echo is transmitted by the ground station acknowledging and granting the request for time slots within the pool of secondary slots available.

DLS

E-TDMA tailors its use of Forward Error Correction to the information being protected as well as its length. For example, header information is proposed to be protected by a BCH(31,16) code. Small slot data is to be protected by a BCH (63,45) code, and long slot data is to be protected by (31,23) Reed Solomon code. SOFREA VIA provides examples of the overhead incurred when CRC and FEC is incorporated for both short and long time slot bursts. For short time slots, 151 data bits appended with 69 CRC bits results in a 46% overhead due to use of CRC while, for long time slots, a 32% penalty applies (1051 data bits and 335 CRC bits). This demonstrates how throughput is managed through tailoring of FEC and error detection for prescribed error rates.

These E-TDMA data integrity features are summarized as follows:

- interleaving for scattering error bursts
- a small number of combinable BCH and RS modules
- target Undetected Error Rate: 10^{-5} to 10^{-6}
- additional CRC at LLC layer with target RER $< 10^{-7}$

3.6.4 Concept of Use: Application to Aeronautical A/G Communications

The concept of use for the Mode 2, Mode 3, Mode E, and Mode 4 systems for aeronautical communications is, by design of these aviation standards, directly as they were intended based on the services provided—voice and/or data. The extension of voice capability to Mode 2 and Mode 4 would require reliable telecommunications infrastructure support from the remote sites to the Air Traffic Control center. The roles of ground infrastructure, avionics, and avionics interfaces to on-board Communications Management Units (CMU's), where applicable with larger aircraft, do not change.

As stated earlier, Mode 2 and Mode 4 provide data service only while Mode 3 and Mode E (prototyped) provide integrated voice and data. When the FCS minimum threshold requirements are applied to these individual systems, additional analyses are required to formulate the concept of usage for each system to accommodate both voice and data capabilities. For this analysis, voice capability will be added to Mode 2 and Mode 4 through a Voice-over-IP (VoIP) protocol since both systems are packet based and a straight-forward means of adding voice to packet-based systems is through use of VoIP. In fact, an RFI response proposed the use of IP over Mode 2. The use of packet switching makes use of the bandwidth that is ordinarily usurped by the guarantee mechanisms for deterministic voice performance over a TDMA system such as Mode 3 with reserved timeslots for voice. This offsetting makes the use of VoIP with packet mode for Modes 2 and 4 a fairer comparison in terms of utilizing bandwidth resources over the VHF spectrum. The capacity increase achieved by any of these systems, if there is any, will be the key discriminator for their utility for future aeronautical communications. The systems and how they would be applied for a voice and data capability is described next along with how these systems would be integrated in the ground infrastructure is described as well.

3.6.4.1 Mode 2

Mode 2 was designed to accommodate data only and for message traffic deemed characteristic of anticipated AOC message traffic for the future. The CSMA protocol employed in Mode 2 not only allows for data collisions, it also provides for collision avoidance. This works well in scenarios with many aircraft sending short messages a periodically. It also can work well when the number of aircraft is low and large messages need to be sent. When the message traffic increases, timers within CSMA p-persistence protocol which control interval wait times between transmissions, can grow quite quickly. As a result, the effect of traffic loading can be severe as the number of messages required to be sent over the channel becomes demanding.

With this limitation understood, and to be fair in this FCS evaluation, a VoIP implementation of voice over a private IP-based network was considered for both Modes 2 and Mode 4 to provide a basis for fairer comparison in support of both voice and data. Since an IP network protocol is a best effort approach for packet delivery, normally the transport layer is used to add protection or reliability mechanisms. For VoIP services, UDP, or User Data Protocol, is typically used as a transport layer protocol for speed of delivery and for a forgiveness factor which voice can often tolerate regarding lost packets. The Address field for Internet Protocol, Version 4 or 6, is 32 bit and 48 bits, respectively; this is more than adequate to handle sectors of any size. If the Mode 2 packet data is wrapped in an IP Version 4 header, the expected overhead of the IP header is 28 bytes. A UDP header consists of 4 header fields consuming 12 additional bytes for source and destination address, length of payload, and checksum fields. If this subtotal of 40 bytes is assumed to be the overhead for the network and for the very minimal transport layers, then the Mode 2 packet, at its burst rate of 31.5 kbps, is now on the order of 10 msec longer, a not unreasonable penalty for overhead for long pulses. If the Mode 2 traffic was composed of primarily shorter bursts, then this overhead could significantly affect the channel loading. The 40 byte overhead is a minimum value as there is not any error detection provided but, for voice, none would probably be used.

Other considerations are the mix of voice and data on the channel. If the channel traffic is mostly data, then voice performance would not be expected to be deterministic for a shared voice and data system not employing voice priority mechanisms (such as is used in Mode 3). This is probably not acceptable for ATC voice traffic and would be a significant issue. A very inefficient scheme for Mode 2 to accommodate both voice and data traffic is use of separate radio frequency channels for voice and data but more deterministic voice performance would result.

The Mode 2 ground infrastructure is composed of digital VHF radios for the 8PSK waveform (produced by at least two vendors) and these radios interface to control boxes which may be remotely located. Today's Mode 2 infrastructure is composed of remote sites that may be shared with ACARS transceivers and antenna systems. The ground telecommunications are composed of both analog and, primarily, digital lines for AOC and ATS services. Note that AOC does include voice and data, in general, although pre-Mode 2 AOC systems carry voice on DSB-AM channels reserved for AOC and data on ACARS channels. Many of these sites have been adapted for Mode 2 with ATN connectivity to ground-to-ground routers. ATS services may be provided on yet another path of infrastructure telecommunications if the AOC services are not adequate. The infrastructure may have to be augmented for the candidate system carrying voice and data traffic for two reasons: 1) ATC voice telecommunications lines originating from ATC voice switches would need to be installed if they are not already and 2) the redundancies in resources such as remote site backup sites and redundant telco may need to be augmented to achieve the system availability required for ATC. This level may not be completely present in today's initial Mode 2 installations although a level adequate for ATC through CPDLC messaging is present.

3.6.4.2 Mode 3 and Mode E

These modes already provide voice and data capability so their concept of use is known. The use of timeslots dedicated for voice and, separately, for data provides deterministic, or predictable, service and comes at a penalty of overhead bandwidth. The system would not be changed as it already possesses voice and data modes and offers some capacity increases.

Integration with existing infrastructure is straightforward in that Multi-Mode Digital Radios (MDR) are in production today that provide current analog DSB-AM interfaces as well as the digital interfaces for Mode 3. Radio Interface Units (RIU) are required for control of the MDR radio. The RIU and MDR interface to the legacy Radio Control Equipment (RCE) used for telco connectivity between the Voice Switch at the control site and the MDR radio at the remote site. The RIU is also the interface to digital telco lines for migration or cutover to full Mode 3 operation. The switchover that must occur when failures happen at remote sites or occur due to telco failure is performed at the control site. Much of the Mode 3 architecture design to permit the required ATN mobility performance and the availability requirements necessary for ATC services was being developed within a program called Rapid Preliminary Development Effort (RPDE) which was to transition to a Full Scale Development program until it was put on hold in mid 2004.

3.6.4.3 Mode 4

The same overhead estimation process used to implement a VoIP function for Mode 2 may be applied, as a first order estimate, to Mode 4 to achieve a voice and data system. It must be assumed that a voice and data system over Mode 4 would be totally separated from surveillance-related message traffic due to the magnitude of messaging in denser airspace where broadcast position reports would be more frequent; another channel(s) is required for this.

If this subtotal of 40 bytes from the IP and UDP header fields is assumed to be the overhead for the network and for the very minimal transport layers, then the Mode 4 packet, at its burst rate of 19.2 kbps, is now on the order of 17 ms longer, a considerable penalty. The short transmission protocol with a 13.3 ms duration would incur nearly 130 % penalty with the extra 17 ms of IP and UDP-induced

overhead so the long transmission protocol is probably more suited for voice packets at the expense of channel access issues for more users sharing the channel. Data mode would be used according to the point-to-point requirements in development presently.

The Mode 4 ground infrastructure and airborne system is presently being architected in Europe although several test sites, especially for ADS-B testing, are operational, including the North European ADS-B Network (NEAN Update Program, Phase 2 (NUP 2)).⁹⁷ The Mode 4 architecture for both ground and air systems will be dependent on the services provided at any regional site. Eurocontrol is investigating these implications on architecture presently. This mix of service configurations is:

- VDL4 for both communications and surveillance applications
- VDL4 for surveillance applications only
- VDL4 for communications applications only

This information is presently being developed through Eurocontrol. Mode 4 is planned to be implemented with a ground station but it should be noted it does not require a ground station; however, reduced performance results from the degraded positioning and time scheduling that results.

Issues for avionics begin with the number of Mode 4-provided services that have to be provided concurrently on an airframe. More than 1 receiver may be located within the same avionics box to accommodate the Mode 4 monitoring requirements for the various mix of Global Signal Channels and Local and Regional Signaling Channels. Avionics certification processes could be complicated depending on the number of radios, their failure mechanisms, the healing modes, and whether avionics are designed to carry more than one software protocol stack. Furthermore, Mode 4 avionics require coordination control busses to provide continuity of services in the event one transceiver unit (of at least two for air transport) fails. This is an additional cost to equip. Some analyses, on the other hand, have estimated this cost to be minimal.

3.6.4.4 *E-TDMA*

E-TDMA utilizes a cellular architecture⁹⁸ of ground stations and is based on cellular concepts. The general attributes of this cellular concept of deployment is summarized as follows:

- cells tailored to operations:
 - air traffic density
 - deployed applications
 - en-route, TMA, airport
- cellular layout description:
 - loaded as pre-flight information
 - periodically broadcast on a GSC
- handover protocol:
 - aircraft-initiated (based on the cellular layout and own position)
 - inter-connected ground stations
- self-insertion mechanism:
 - for popping-up aircraft
 - as a backup or alternative to handover

The obvious characteristic of this system which is different from the other VDL subnetworks is that E-TDMA requires a priori knowledge of ground station position by the aircraft receiver. In today's VHF ATC and AOC systems, the ground station is implicitly identified through use of a "pre-loaded" channel map by sector. In other words, the pilot knows a priori which channel to tune to by virtue of knowledge of the sector being traversed. The E-TDMA system's use of cellular concepts might be somewhat different

than the remote site density planning employed today. This may have an impact on ground architecture and cost.

By using the aircraft's knowledge of position through Relative Navigation Performance (RNP) as well as published ground station coordinates, its position relative to all the local ground stations are known. This knowledge facilitates air-initiated, ground-coordinated handovers for mobility management. This knowledge, as stated earlier, is important when recovering from a ground or air station failure in that warm start procedures may be used in certain cases, speeding recovery times.

Normal aircraft insertion into the network, when not being handed off by another ground station, into a new sector is handled by use of Hello mini-slots for request to enter the network. These are dedicated primary slots. The ground station echoes back with approval in a later timeslot. The p-persistent CSMA MAC protocol scheme, similar to that used in Mode 2, with collision detection, is used to access the channel during this phase. The number of Hello mini-slots needed to achieve high levels of success for insertion within 1 E-TDMA cycle is a design parameter but ranges from 12 to 156 depending on number of aircraft attempting to enter per cycle, and the probability of success value.

E-TDMA does not require use of a ground station so its protocol must provide for continuous communications for broadcast and addressed air-to-air traffic. Note that the ground station is the one of the normal source for monitoring and adjusting timing within the airborne radio. It must do so when the number of aircraft is low such that timing maintenance must be adequately performed. The E-TDMA concept provides for an autonomous mode for any of the following reasons: 1) where no ground station is present, 2) where aircraft density is low, 3) for local mode broadcast and addressed air-to-air functions only. The autonomous operational mode is described next.

Within the E-TDMA cycle, contiguous slots are appropriated for various levels of QoS. The secondary slots within the QoS_i^{th} window of slots described earlier are shared among N aircraft, who all share a common modulo count K_i . When the number of aircraft reaches N , at most N/K_i aircraft may request and queue slots for use. For insertion, or net entrance, aircraft announce their arrival through short arrival broadcast messages in free primary slots. These announcements, in turn, are re-broadcast by other aircraft throughout the sector by back-propagation. A re-broadcast counter is decremented after use by each aircraft to limit the back-propagation volume.

A distributed QoS monitoring process is used to contribute to E-TDMA's QoS service guarantees. One item is that of a slot occupancy map constructed by the airborne radio to facilitate slot scheduling and event reporting and monitoring. The use of deterministic slot assignments is important for QoS performance. The second is use of short message broadcast fields for reporting of anomalous events. The monitoring of the airborne equipment of this reported information permits QoS alarms to be sounded when thresholds of performance are not met.

Ground infrastructure for E-TDMA would utilize a density of remote site similar to that planned for the other VHF subnetworks. Avionics, it was mentioned earlier, need to carry multiple receivers for monitoring of GSC's and for ADS-B sub-functions. It probably can be safely assumed that the architecture and the cost for airborne equipment would be similar to that planned for Mode 4.

The E-TDMA concept proposed by SOFREAVIA is a data-only system that, by their assessment, might be adapted to provide voice capability. For the purposes of this evaluation phase, a voice capability will be assumed to be implemented for the same reasons it was added for Modes 2 and 4. A VoIP technique might be applied to the E-TDMA protocol, but with some qualifications. A scheduled voice conversation will probably have to be implemented in a natural extension of the reservation process for data slots as described earlier. This is due to the E-TDMA deterministic performance of slot assignments advertised by

SOFREAVIA. For this reason, latency of voice due to access time would be at issue. It will be assumed that the current reservation of slots for data could be utilized for voice slots with the addition of a voice signaling field in the reservation message. Another option is the addition of a reserved slot for voice scheduling to provide the deterministic nature required for ATC voice traffic. The overhead for the network layer portion of IP is assumed to be similar to that used for the Mode 2 and Mode 4 analysis.

3.6.5 Evaluation Summary and Scores

The candidate systems that were evaluated within the VHF narrowband services family consist of Mode 2 with VoIP, Mode 3, Mode 3 with SAIC, Mode E, and Mode 4 with VoIP. The evaluation for Mode 3 with SAIC is identical to that of Mode 3 and is not presented here. The evaluation criteria did not possess sufficient resolution in the area of capacity to affect the numerical evaluation. The other members will be presented, first in terms of its broad performance within each category and second, the rationale that supports the color coding for the evaluation in each evaluation category.

Table 3.6-3 provides the scoring summary for Mode 2 with VoIP. The rationale for the assigned scores is provided in table 3.6-4.

Table 3.6-3: VDL Mode 2 with VoIP Evaluation Worksheet

	Criteria	Surface	Terminal	En Route	Oceanic	Polar
Voice Needs	1					
Pilot-Controller Talk Group	1A1					
Pilot-Controller Selective Addressing	1A2					
Direct Pilot-Pilot	1A3					
Broadcast capability	1A4					
Capacity provided	1B1					
Address space	1B3					
Aircraft mobility management	1C1					
Latency	1C2					
Basic Data Needs	2					
A/G and G/A Addressed Data Transport	2A1					
Ground-to-Air Broadcast Data Transport	2A2					
Aggregate Data Rate	2B1					
Number of Users	2B2					
Uplink and Downlink Priority Levels / QoS	2C1					
Latency	2C2					
Enhanced Data	3					
ADS-B	3A1					
Pilot-Pilot Data Transport	3A2					
Aggregate Data Rate	3B1					
Technology Readiness Level	4					
Standardization Status	5					
Certifiability	6					
Ground Infrastructure Cost	7					
Cost to Aircraft	8					
Spectrum Protection	10					
Security	11					
Transition	12					

Table 3.6-4: Mode 2 with VoIP Scoring Rationale

Element	Score	Rationale
Pilot-Controller Talk Group	Yellow (S, T, E) Red (O and P)	Does not presently support voice. Modification required to support using packet-based service using VoIP may support this feature. IP header with source and destination addressing using protocol would permit conference call feature.
Pilot-Controller Selective Addressing	Yellow (S, T, E) Red (O and P)	Does not presently support voice. Modification required. Source/Destination address in IP header with a "privacy" bit field used would provide a direct addressing feature with privacy feature. Four bytes available in IPv4 header for optional assignment could be used for privacy bit. Requires ground station so oceanic/polar not serviced.
Direct Pilot-Pilot	Yellow (all domains)	Does not presently support voice. Modification required. Source/Destination address in IP header with a "privacy" bit field used would provide a direct addressing feature with privacy feature. Four bytes available in IPv4 header for optional assignment could be used for privacy bit.
Broadcast capability	Yellow (S, T, E) Red (O and P)	Does not presently support voice. Modification required. Packet ID for broadcast packets and even multi-cast could be implemented as it is for VoIP protocol.
Capacity provided	Red (all domains)	Number of simultaneous user channels does not increase within VHF AM(R)S band with CSMA using LBPTT—higher overhead inefficiency with CSMA protocol. IP and UDP header overhead used in comparative analysis estimated to be at least 10 msec. Capacity low especially if shared with data.
Address space	Green (all domains)	Not a limiting factor since packet source and destination address ID field in IP header is 32 bits (IPv4) and 48 bits (IPv6).
Aircraft mobility management	Green (S, T, E) Red (O and P)	Mode 2 supports mobility (handoff, etc.) through compliance with ATN mobility requirements (IDRP, etc.) and support for voice would only require minimal standards work.
Latency	Red (all domains)	Unlikely that a VoIP over VDL Mode 2 could meet the 400 ms delay when overhead allowance is made for collisions and buffering and considering mechanisms to allow multiple users to share channel. Typically, VoIP has fairly large buffering requirements.
A/G and G/A Addressed Data Transport	Green (S, T, E) Red (O and P)	Mode 2 standard supports addressed data. Needs ground station—polar/oceanic not supported.
Ground-to-Air Broadcast Data Transport	Green (S, T, E) Red (O and P)	Presently supported in Mode 2 standard for data as with broadcast ATS services, e.g. FIS-B-DL. Needs ground station.
Aggregate Data Rate	Yellow (all domains)	Fixed at 31.5 kbps raw channel burst data rate but with CSMA MAC, throughput is less than 20 kbps.
Number of Users	Green (all domains)	Not bounded by address space for aircraft ID (24 bit ICAO address used in Mode 2 standard)
Uplink and Downlink Priority Levels/QoS	Red (all domains)	QoS for Mode 2 not deterministic and priority is not supported. Not specified how priority would be supported or how QoS would be managed especially for ATC applications for a CSMA-based protocol with permissible longer packets.
Latency	Green (all domains)	Delay typically meets CPDLC latency criterion for most domains acc. to studies. Delay is a function of load presented to Mode 2: where load is a function of data mix, number of users, etc. Studies (e.g. GRC and Cleveland State Univ.) indicate Mode 2 cannot support certain mixes of traffic for the expected number of aircraft for certain types of domains.
ADS-B	Red (all domains)	Standard does not support this and CSMA with packet latency and non-deterministic QoS would preclude a surveillance function especially under high traffic conditions.
Pilot-Pilot Data Transport	Yellow (all domains)	Standard does not support this, but air-air communications could be provided using the SVC mode for data exchanges with the ground as intermediary or possibly direct air-to-air.
Aggregate Data Rate	Red (all domains)	Fixed 31.5 kbps raw channel burst rate is effectively lower when averaged over time
Technology Readiness Level	Green	Mode 2 for CPDLC with certified avionics on major airlines is being used through ARINC and SITA at Miami ARTCC as well as Link 2000+ and through several European (NEAN UPII) and Mediterranean (MEDUP) test and evaluation sites and Japan, among others.
Standardization Status	Green	Mode 2 is a rather mature aviation standard with SARPS, MOPS, MASPS, AEEC etc.
Certiability	Green	Mode 2 ground equipment have been produced and avionics have been certified. More than one vendor for each is on the marketplace.
Ground Infrastructure Cost	Green	Relative cost is same as that for today due to VHF equipment in use today and nature of VHF sectors and deployment.
Cost to Aircraft	Green	Present day multi-mode avionics are slightly more expensive than DSB-AM-only radios. Number of radios/aircraft expected to be same as DSB-AM.
Spectrum Protection	Green	Mode 2 already approved for 136 to 136.975 MHz and with FCC emission designation and compatible with 25 kHz channelization of rest of VHF AMRS band.
Security	Yellow	Mode 2 can be modified to provide authentication and integrity at the application layer.
Transition	Green	Supports incremental deployment

Table 3.6-5 provides the scoring summary for Mode 3. The rationale for the assigned scores is provided in table 3.6-6.

Table 3.6-5: Mode 3 Evaluation Worksheet

	Criteria	Surface	Terminal	En Route	Oceanic	Polar
Voice Needs	1					
Pilot-Controller Talk Group	1A1					
Pilot-Controller Selective Addressing	1A2					
Direct Pilot-Pilot	1A3					
Broadcast capability	1A4					
Capacity provided	1B1					
Address space	1B3					
Aircraft mobility management	1C1					
Latency	1C2					
Basic Data Needs	2					
A/G and G/A Addressed Data Transport	2A1					
Ground-to-Air Broadcast Data Transport	2A2					
Aggregate Data Rate	2B1					
Number of Users	2B2					
Uplink and Downlink Priority Levels / QoS	2C1					
Latency	2C2					
Enhanced Data	3					
ADS-B	3A1					
Pilot-Pilot Data Transport	3A2					
Aggregate Data Rate	3B1					
Technology Readiness Level	4					
Standardization Status	5					
Certifiability	6					
Ground Infrastructure Cost	7					
Cost to Aircraft	8					
Spectrum Protection	10					
Security	11					
Transition	12					

Table 3.6-6: Mode 3 Scoring Rationale

Element	Score	Rationale
Pilot-Controller Talk Group	Green (S, T, E) Red (O and P)	By requirement, Mode 3 supports party line operation and User Talk Groups maybe separated by sector—nature of ground control precludes oceanic and polar operation.
Pilot-Controller Selective Addressing	Yellow (S, T, E) Red (O and P)	Not presently provided. Judged as a “moderate” modification because the voice header bit field allowance is packed. No new message ID is achievable. A conceivable change is to require ground transmissions to use the GSC in the “Local User ID” field for group conference call voice messages (normal or party line voice functionality) and the address of the AC for “Selective Addressing” calls. However, this only provides 1-way addressed functionality, which is not the intent of this functional requirement. Robbing the 2-bit slot ID seems to be an option, but this might impact other modes of operation, specifically 1V3D.
Direct Pilot-Pilot	Green (all domains)	By requirement, Mode 3 supports this through party line operation—voice does not require an intermediary. Timing State 1 voice provided when ground station present with adequate signal and slightly degraded voice operation potential when no reference timing source/ground station present.
Broadcast capability	Green (S, T, E) Red (O and P)	Ground-to-air broadcast with controller over-ride feature provided.
Capacity provided	Green (all domains)	4 slot, 4V mode, TDMA operation with guard bands will result in at least factor of 2 increase.
Address space	Green (all domains)	1V3D supports up to 240 addressed aircraft in one (large) user group.
Aircraft mobility management	Green (S, T, E) Red (O and P)	Mobility management already supportable by design and requirement through ATN in coverage areas
Latency	Green (all domains)	Latency of voice in most scenarios will meet 250 msec. Some ground architectures will be somewhat longer.
A/G and G/A Addressed Data Transport	Green (S, T, E) Red (O and P)	By Mode 3 requirement.
Ground-to-Air Broadcast Data Transport	Green (S, T, E) Red (O and P)	By Mode 3 requirement.
Aggregate Data Rate	Yellow (all domains)	Burst rate is 31.5 kbps but user data rate is 4800 bps in 2V2D; even 1V3D will not support 20 kbps throughput.
Number of Users	Green (all domains)	Supports up to 240 addressed users
Uplink and Downlink Priority Levels/QoS	Green (all domains)	4 level priority and priority grouping of frames performed, latency controlled through addressed data mode and ACK behavior.
Latency	Green (all domains)	Data transport delay designed to support ATN requirements for critical ATC.
ADS-B	Red (all domains)	Data exchange between aircraft not currently defined. Defining new protocols for A/A data in support of surveillance and with adequate update rates not seen as a moderate modification.
Pilot-Pilot Data Transport	Red (all domains)	Data exchange between aircraft not currently defined. Defining a new protocol for A/A data mode seen as more than moderate modification.
Aggregate Data Rate	Red (all domains)	Fixed 31.5 kbps raw channel burst rate is effectively considerably lower when averaged over time for all the various operational VDL3 modes and is a maximum for the 3T mode but does not rise to the threshold for extended aggregate data rate
Technology Readiness Level	Green	Production ground equipment available and Mode 3-capable red label avionics for transport and GA aircraft available. Flight tests have been conducted, and system interoperability tests occurred in 2003 under FAA oversight.
Standardization Status	Green	SARPS, MASPS, and MOPS approved.
Certifiability	Green	Avionics certification nearly complete. Vocoder and avionics close to black (production) label-ready.
Ground Infrastructure Cost	Green	Relative cost estimated to be baseline against any new digital candidate system. Given green to reflect this.
Cost to Aircraft	Green	Relative cost estimated to be baseline against any new digital candidate system. Given green to reflect this.
Spectrum Protection	Green	Allocation already approved with FCC emission designation in VHF AM(R)S band.
Security	Yellow	Mode 3 can be modified to provide authentication and integrity at the application layer.
Transition	Green	Supports incremental deployment

Table 3.6-7 provides the scoring summary for Mode E. The rationale for the assigned scores is provided in table 3.6-8.

Table 3.6-7: Mode E Evaluation Worksheet

	Criteria	Surface	Terminal	En Route	Oceanic	Polar
Voice Needs	1					
Pilot-Controller Talk Group	1A1					
Pilot-Controller Selective Addressing	1A2					
Direct Pilot-Pilot	1A3					
Broadcast capability	1A4					
Capacity provided	1B1					
Address space	1B3					
Aircraft mobility management	1C1					
Latency	1C2					
Basic Data Needs	2					
A/G and G/A Addressed Data Transport	2A1					
Ground-to-Air Broadcast Data Transport	2A2					
Aggregate Data Rate	2B1					
Number of Users	2B2					
Uplink and Downlink Priority Levels / QoS	2C1					
Latency	2C2					
Enhanced Data	3					
ADS-B	3A1					
Pilot-Pilot Data Transport	3A2					
Aggregate Data Rate	3B1					
Technology Readiness Level	4					
Standardization Status	5					
Certiability	6					
Ground Infrastructure Cost	7					
Cost to Aircraft	8					
Spectrum Protection	10					
Security	11					
Transition	12					

Table 3.6-8: Mode E Scoring Rationale

Element	Score	Rationale
Pilot-Controller Talk Group	Green (S, T, E) Red (O and P)	By requirement, Mode E supports party line operation and User Talk Groups maybe separated by sector—nature of ground control precludes oceanic and polar operation.
Pilot-Controller Selective Addressing	Yellow (S, T, E) Red (O and P)	Not presently provided. Judged as a “moderate” modification because the voice header bit field allowance is packed. No new message ID is achievable. A conceivable change is to require ground transmissions to use the GSC in the “Local User ID” field for group conference call voice messages (normal or party line voice functionality) and the address of the AC for “Selective Addressing” calls. However, this only provides 1-way addressed functionality, which is not the intent of this functional requirement. Robbing the 2-bit slot ID seems to be an option, but this might impact other modes of operation, specifically 1V3D.
Direct Pilot-Pilot	Green (all domains)	By requirement, Mode E supports this through party line operation—voice does not require an intermediary. Timing State 1 voice provided when ground station present with adequate signal and slightly degraded voice operation potential when no reference timing source/ground station present.
Broadcast capability	Green (S, T, E) Red (O and P)	Ground-to-air broadcast with controller over-ride feature provided.
Capacity provided	Green (all domains)	For 2 slot, 2V mode, and replacing a 25 kHz AM circuit, Mode E TDMA operation with 3 x 8.33 kHz assignments in existing 25 kHz channel (guard bands for freq planning only partially accounted for) will result in factor of 6 increase according to Rockwell-Collins. A 1V1D mode will result in less. Insertion into European airspace with existing 8.33 kHz AM channels limited to maximum increase of factor of 2 (without accounting for guard bands).
Address space	Yellow (all domains)	Address space presently limited to 128 airborne users—bit field width-limited presently for TDMA may preclude straightforward increase in address space
Aircraft mobility management	Green (S, T, E) Red (O and P)	Mobility management already supportable by design and requirement through ATN in coverage areas
Latency	Green (all domains)	Latency of voice in most scenarios will meet 250 ms. Some ground architectures will be somewhat longer.
A/G and G/A Addressed Data Transport	Green (S, T, E) Red (O and P)	By Mode 3 requirement and, therefore, by Mode E requirement.
Ground-to-Air Broadcast Data Transport	Green (S, T, E) Red (O and P)	By Mode 3 requirement and, therefore, by Mode E requirement.
Aggregate Data Rate	Yellow (all domains)	Burst rate is 31.5 kbps but user data rate is 4800 bps in 1V1D; will not support 20 kbps throughput.
Number of Users	Green (all domains)	Aircraft stations uniquely specified by 24 bit ICAO address
Uplink and Downlink Priority Levels/QoS	Green (all domains)	4 level priority and priority grouping of frames performed, latency controlled through addressed data mode and ACK behavior.
Latency	Green (all domains)	Data transport delay designed to support ATN requirements for critical ATC.
ADS-B	Red (all domains)	Data exchange between aircraft not currently defined. Defining new protocols for A/A data in support of surveillance and with adequate update rates not seen as a moderate modification.
Pilot-Pilot Data Transport	Red (all domains)	Data exchange between aircraft not currently defined. Defining new protocols for A/A data not seen as a moderate modification.
Aggregate Data Rate	Red (all domains)	Data rate limited to 15.75 kbps burst rate and 4800 bps raw user rate for 1V1D mode.
Technology Readiness Level	Green	Mode 3 production ground equipment is available and Mode 3-capable red label avionics for transport and GA aircraft is available. Adding a Mode E capability does not degrade the TRL level since relatively minor, low risk, physical layer changes are required to transition to the high TRL state of Mode 3 pre-production avionics and production ground radio status today. Furthermore, advanced Mode 3 flight tests have been conducted, and system interoperability tests occurred in 2003 under FAA oversight adding to the green assessment of TRL for Mode E-capable avionics
Standardization Status	Green	Green rating given to reflect the advanced status of aviation-approved Mode 3 SARPS, MASPS, and MOPS and that changes to accommodate Mode E are deemed low risk and would be expected to be performed within a rapid timeframe.
Certifiability	Green	Avionics certification for Mode 3 nearly complete but Mode E software would need additional certification process. This is deemed low risk in light of Mode 3 cert progress. In addition, vocoder stays the same as for Mode 3.

Element	Score	Rationale
Ground Infrastructure Cost	Green	Relative cost estimated to be baseline against any new digital candidate system. Given green to reflect this.
Cost to Aircraft	Green	Relative cost estimated to be baseline against any new digital candidate system. Given green to reflect this.
Spectrum Protection	Green	Allocation already approved with FCC emission designation in VHF AM(R)S band.
Security	Yellow	Mode E can be modified to provide authentication and integrity at the application layer.
Transition	Green	Supports incremental deployment

Table 3.6-9 provides the scoring summary for Mode 4 with VoIP. The rationale for the assigned scores is provided in table 3.6-10.

Table3.6-9: Mode 4 with VoIP Evaluation Worksheet

	Criteria	Surface	Terminal	En Route	Oceanic	Polar
Voice Needs	1					
Pilot-Controller Talk Group	1A1					
Pilot-Controller Selective Addressing	1A2					
Direct Pilot-Pilot	1A3					
Broadcast capability	1A4					
Capacity provided	1B1					
Address space	1B3					
Aircraft mobility management	1C1					
Latency	1C2					
Basic Data Needs	2					
A/G and G/A Addressed Data Transport	2A1					
Ground-to-Air Broadcast Data Transport	2A2					
Aggregate Data Rate	2B1					
Number of Users	2B2					
Uplink and Downlink Priority Levels / QoS	2C1					
Latency	2C2					
Enhanced Data	3					
ADS-B	3A1					
Pilot-Pilot Data Transport	3A2					
Aggregate Data Rate	3B1					
Technology Readiness Level	4					
Standardization Status	5					
Certiability	6					
Ground Infrastructure Cost	7					
Cost to Aircraft	8					
Spectrum Protection	10					
Security	11					
Transition	12					

Table 3.6-10: Mode 4 with VoIP Scoring Rationale

Element	Score	Rationale
Pilot-Controller Talk Group	Yellow (S, T, E) Red (O and P)	Mode 4 designed as data-only service. Modification required. Voice mode is possible using STDMA with a VoIP-like mode (packet oriented since there are no actual fixed time slot boundaries). Voice and data probably not wise to integrate onto single Mode 4 channel when scenario loadings for 2015 terminal airspace are assumed. Separate voice capability using Mode 4 on separate voice channel possible although protocol work to date driven by data mode and desired QoS.
Pilot-Controller Selective Addressing	Yellow (S, T, E) Red (O and P)	Modification required. ICAO 24 bit address is used for aircraft ID and would facilitate air-to-air voice mode or destination address in IP header would serve this purpose.
Direct Pilot-Pilot	Yellow (all domains)	Air-to-air mode inherent in Mode 4 protocol—does not require ground intermediary. Modification required for voice.
Broadcast capability	Yellow (S, T, E) Red (O and P)	Mode 4 protocol has an inherent ground and air broadcast mode as part of ADS-B function and for planned point-point data mode. Since terrestrial ground station is implied, polar/oceanic broadcast service not provided.
Capacity provided	Red (all domains)	Assigning Mode 4 to a 25 KHz channel could support no more than a single voice channel. This conclusion is based on VoIP overhead in header (see report text) compared to Mode 4 slot times.
Address space	Green (all domains)	IP destination address or use of ICAO 24 bit address used for aircraft ID in Mode 4 data protocol results in virtually unlimited address space.
Aircraft mobility management	Green (S, T, E) Red (O and P)	Mobility management will be, by design and requirement, handled through ATN in coverage areas
Latency	Green (all domains)	Latency of voice mode would be a little more than that for Mode 3 due to reservation scheduling overhead and non-deterministic nature. Voice-only channel assumed—sharing voice with data appears problematic due to traffic and contention issues.
A/G and G/A Addressed Data Transport	Green (S, T, E) Red (O and P)	By Mode 4 requirement for point-to-point data link mode.
Ground-to-Air Broadcast Data Transport	Green (S, T, E) Red (O and P)	By Mode 4 requirement for point-to-point data link mode.
Aggregate Data Rate	Yellow (all domains)	Burst rate is 19.2 kbps.
Number of Users	Green (all domains)	Virtually unlimited through use of 24 bit ICAO address plus 3 bit mapping field
Uplink and Downlink Priority Levels/QoS	Green (all domains)	Should be possible, as 15 level priority (ungrouped) is provided in protocol and message latency appears through simulations to satisfy scenarios through 2015
Latency	Green (all domains)	Should be responsive according to many simulation studies to date.
ADS-B	Green (all domains)	Mode 4 standard supports this as it was geared primarily to provide this from its inception.
Pilot-Pilot Data Transport	Green (all domains)	Standards work ongoing to provide for air-to-air data communications—implementation appears feasible.
Aggregate Data Rate	Red (all domains)	Mode 4 is narrowband and burst data rate is only 19.2 kbps.
Technology Readiness Level	Green	Considered TRL of 6 since flight tests have been and are being conducted for ADS-B and broadcast services along with extensive simulations in support of throughput, latency as a function of traffic loading.
Standardization Status	Green	Aviation standards exist—SARPS being drafted for Mode 4 as a point-to-point data communications subnetwork (SARPS already approved for ADS-B surveillance)
Certifiability	Green	Certification for VLD Mode 4 is in a certification process within Europe.
Ground Infrastructure Cost	Green	VHF band favorable for retaining existing density of ground stations. Cost of ground equipment assumed to be similar to other VDL Mode x ground equipment. Cost impact, if any, due to coordination of ground transmissions for broadcast services for relatively closely spaced ground stations is unknown.
Cost to Aircraft	Green	Estimated cost is equal to 1.1 x ARINC 716 8.33/25 kHz DSB-AM analog receiver.
Spectrum Protection	Green	Proposed for the AM(R)S band for point-to-point data link usage. Narrowband waveform supports this.
Security	Yellow	Authentication and integrity typically handled at ATN level.
Transition	Green	Supports incremental deployment.

Table 3.6-11 provides the scoring summary for E-TDMA. The rationale for the assigned scores is provided in table 3.6-12.

Table 3.6-11: E-TDMA Evaluation Worksheet

	Criteria	Surface	Terminal	En Route	Oceanic	Polar
Voice Needs	1					
Pilot-Controller Talk Group	1A1					
Pilot-Controller Selective Addressing	1A2					
Direct Pilot-Pilot	1A3					
Broadcast capability	1A4					
Capacity provided	1B1					
Address space	1B3					
Aircraft mobility management	1C1					
Latency	1C2					
Basic Data Needs	2					
A/G and G/A Addressed Data Transport	2A1					
Ground-to-Air Broadcast Data Transport	2A2					
Aggregate Data Rate	2B1					
Number of Users	2B2					
Uplink and Downlink Priority Levels / QoS	2C1					
Latency	2C2					
Enhanced Data	3					
ADS-B	3A1					
Pilot-Pilot Data Transport	3A2					
Aggregate Data Rate	3B1					
Technology Readiness Level	4					
Standardization Status	5					
Certiability	6					
Ground Infrastructure Cost	7					
Cost to Aircraft	8					
Spectrum Protection	10					
Security	11					
Transition	12					

Table 3.6-12: E-TDMA Scoring Rationale

Element	Score	Rationale
Pilot-Controller Talk Group	Green (S, T, E) Red (O P)	E-TDMA designed as data-only service. Modification required will impact data mode. Voice mode is possible using STDMA with a VoIP-like mode (packet oriented). Voice and data probably not wise to integrate onto single E-TDMA channel when scenario loadings for 2015 terminal airspace are assumed. Separate voice capability using E-TDMA on separate voice channel possible although protocol concept driven by data mode and desired QoS maintenance.
Pilot-Controller Selective Addressing	Green (S, T, E) Red (O P)	Modification to data concept required. ICAO 24 bit address could be used for aircraft ID and would facilitate air-to-air voice mode or destination address in IP header would serve this purpose. Protocol is not defined yet so a bit field controlling selective listening/addressing is possible.
Direct Pilot-Pilot	Green (all domains)	Air-to-air mode inherent in Mode 4 protocol—does not require ground intermediary. Modification required for voice.
Broadcast capability	Green (S, T, E) Red (O P)	E-TDMA, by design for data mode, possesses an inherent ground and air broadcast mode as part of ADS-B function and for planned generic data mode. Protocol, not defined to date, could be designed to accommodate voice broadcast mode. Since terrestrial ground station is implied, polar/oceanic broadcast service not provided.
Capacity provided	Red (all domains)	Insufficient information provided by proposal. Assessed at none to little increase in voice capacity possible due to use of scheduling overhead and QoS demarcation intervals of frame—when shared with data services, any increase in voice capacity is very questionable. Will be significantly degraded if shared usage with data mode within a given channel. Given a red correspondingly as protocol concept is heavily based on data mode and modifications would be significant impact to concept.
Address space	Green (all domains)	IP destination address or use of ICAO 24 bit address used for aircraft ID in Mode 4 data protocol would result in virtually unlimited address space.
Aircraft mobility management	Green (S, T, E) Red (O P)	Mobility management will be, by design and requirement, handled through ATN. E-TDMA would have to be developed to satisfy ATN routing requirements and would be accommodated according to concept provider. Mobility managed through air-initiated, ground coordinated scheme and also through autonomous (without aid of ground station) mode.
Latency	Green (all domains)	Latency of voice mode would be somewhat more than that for Mode 3 due to reservation scheduling overhead if voice only channel is assumed. Given green on this basis. When shared with data, demarcating frames by QoS levels allocates voice (conceptually) to specific portions of a rather long cycle time when shared with other data services. This will contribute to latency.
A/G and G/A Addressed Data Transport	Green (S, T, E) Red (O and P)	By design requirement for point-to-point data link mode.
Ground-to-Air Broadcast Data Transport	Green (S, T, E) Red (O and P)	By design requirement for point-to-point data link mode.
Aggregate Data Rate	Yellow (all domains)	No information was provided for data rate so VDL Mode 2/3 burst rate is assumed since PHYS layer proposed to use D8PSK.
Number of Users	Green (all domains)	Virtually unlimited through possible use of 24 bit ICAO address.
Uplink and Downlink Priority Levels/QoS	Green (all domains)	Should be possible, as E-TDMA concept focus is on QoS enabling mechanisms.
Latency	Green (all domains)	Should be responsive according to an early simulation.
ADS-B	Green (all domains)	E-TDMA concept aimed at providing this from its inception.
Pilot-Pilot Data Transport	Green (all domains)	Air-to-Air addressed data mode advertised.
Aggregate Data Rate	Red (all domains)	E-TDMA is narrowband and proposed for insertion into 25 kHz channels so this precludes high rate operation.
Technology Readiness Level	Red	Considered TRL of 2 since no hardware design performed to date and only a software model of loading has apparently been performed probably including the MAC layer and its attributes. Maps to a '1' for TRL of 3 or less.
Standardization Status	Red	No standards exist as this is only a concept. Would be designed to aviation standards from early on but none to date. Standards would need to be built from ground up.
Certifiability	Green	Certification process likely to be comparable to any other VDL system, especially Mode 4.
Ground Infrastructure Cost	Green	VHF band favorable for retaining existing density of ground stations. Cost of ground equipment assumed to be similar to other VDL Mode x ground equipment. Cost impact, if any, due to coordination of ground transmissions for broadcast services.

Element	Score	Rationale
Cost to Aircraft	Green	Chuck LaBerges assessment of Mode 4 avionics should be comparable for E-TDMA assessment where Mode 4 estimate indicates cost is equal to 1.1 x ARINC 716 8.33/25 kHz DSB-AM analog receiver.
Spectrum Protection	Green	Proposed for the AM(R)S band for point-to-point data link usage. Narrowband waveform supports this.
Security	Yellow	Authentication and integrity typically handled at ATN level.
Transition	Green	Supports incremental deployment.

3.7 Custom Wide Band

3.7.1 Overview of the Family

This section provides details and background on the custom wideband communications systems that were evaluated as candidates for the Future Aeronautical Communications System. The systems that were evaluated were either proposed to the ICAO Aeronautical Communications Panel, Working Group C (such as B-VHF and ADL); or proposed in response to a NASA RFI (such as FLASH-OFDM); or suggested by the FAA (such as UAT and Mode-S).

This section presents an overview of these technologies. Not all of these systems appeared to provide real value in consideration of a technology applicable for the Future Aeronautical Communications System. As a consequence, some systems were eliminated from detailed evaluation. Those that were selected for evaluation are described in detail, in order to provide the technical basis for the technology evaluations. Technology descriptions include the communications services that are provided, key features, system functional architecture, and the air interface. This leads to a description of the concept of use of this technology for providing aeronautical A/G communications, including a notional physical architecture and applicable services.

Finally, the technologies are then evaluated and scored. From the scoring, some observations are offered that complement the evaluations and provide the authors insight as to the applicability of a technology to the functional, performance and institutional requirements of the Future Aeronautical Communications System.

3.7.2 Selection of Evaluation Candidates via Minimum Threshold Test

Table 3.7-1 provides the systems that were considered in this family of technologies, specifies whether they were selected for evaluation, and provides the rationale.

Table 3.7-1: Rationale for Selection Custom Broadband Candidate Solutions

System	Evaluate	Rationale
Custom Broadband Technologies		
ADL	Yes	Only custom surface domain candidate
Flash-OFDM	No	Proprietary technology that offers potential; however, the details of the technology are obscure. Other multi-user forms of OFDM that are defined in open literature are under consideration for the Future Aeronautical Communications System. In evaluating these technologies, a trade of DSS and FH will be conducted.
UAT	Yes	This system is being standardized by ICAO and provides Air-Air broadcast communications
Mode-S	Yes	Standardized system than is used to provide ADS-B.
Broadband MC-CDMA derived-(B-VHF)	Yes	Promising developmental system

3.7.3 Technology Description

Brief descriptions of ADL, B-VHF, UAT and Mode-S are provided in the following sub-sections.

3.7.3.1 ADL Description

The Advanced Airport Data Link (ADL) started as a research and development program at the German Aerospace Center (DLR). Initial development was conducted in the framework of their TARMAC (Taxi and Ramp Management and Control) program, which was the DLR contribution to A-SMGCS (Advanced Surface Movement and Guidance Communications System) development. The key goals of TARMAC were to decrease the environmental impact of running engines by decreasing waiting times of aircraft, improve the overall throughput on airports by planning routes from runways to gates and vice versa, and to improve the situation awareness of pilots and, thus, improving safety on the airport surface.

From these TARMAC goals, the requirements of the ADL system were derived. These requirements were to provide:

- High transmission bit rate, at least 128 kbit/s per user
- High user capacity, at least 100 simultaneously active users
- Large coverage area, 50 to 100 km around airport
- Data link available during take-off and landing
- Connection to airport intranet
- Expansion toward additional services, e.g., catering orders, airline instructions, aircraft attendance information exchange
- Different priorities for different kinds of services
- Flexibility of physical layer
- Exchange between user capacity and transmission bit rate

To meet these requirements, a system design was specified. The ADL specification provided a high data rate system implemented using Multi-carrier CDMA in the MLS Band (C Band). Details of the air interface specification for ADL are provided in table 3.7-2.

Table 3.7-2: ADL Air Interface Parameters

Parameter	Value
Carrier frequency	5.1465 GHz
Bandwidth	8192 kHz
Number of subcarriers	2048
Subcarrier spacing	4 kHz
OFDM symbol duration	250 μ s
Guard interval duration	10 μ s
Modulation type	QPSK
Spreading length	8
Number of users	128 ... 864
Bit rate per user	128 ... 2048 kbit/s

3.7.3.2 B-VHF Description

B-VHF is a proposal for a future aeronautical ATC communications system which is currently developed within the FP6 European research project B-VHF ("Broadband VHF Aeronautical Communications System Based on MC-CDMA"). The stated goal of the B-VHF project is to verify the feasibility of a broadband VHF aeronautical communications system based on the MC-CDMA technology.

The B-VHF Project is 50% funded by the European Commission Framework Program for Research and Technological Development. In furthering the goals of B-VHF, a B-VHF consortium has been developed. This consortium provides a mix of ATM stakeholders:

- ATM service provider—NATS
- Airline and aeronautics communication equipment provider—Lufthansa and Frequentis
- Research organizations
 - DLR
 - BAES
 - Scientific Generics
 - Ghent University
 - Polytechnic University Madrid
 - University Salzburg
 - DFS
 - University Las Palmas

Publicly available documentation from the B-VHF web site indicates the following work areas of either completed, or ongoing B-VHF development work:

- WP 0 “Project Management and Quality Assurance”—management activities
- WP 1 “B-VHF System Aspects”—High-level requirements for the B-VHF system, and B-VHF Operational Concept document
- WP 2 “VHF Band Compatibility Aspects”—Modeling and measurements of sharing the VHF spectrum
- WP 3 “B-VHF Design and Evaluation”—System design modeling, including broadband VHF channel, physical B-VHF layer, DLL layer, and higher protocol layers
- WP 4 “B-VHF Testbed”—Baseband implementation and evaluation of a B-VHF testbed

While visible work products exist for WP0 and WP1, including a set of comprehensive functional and performance requirements, WP 2, 3 and 4 are clearly ongoing, and no preliminary results are available at this time. The work looks to be a natural continuation of the earlier work conducted by DLR on the ADL, and the initial system concept calls for MC-CDMA and FDM techniques being applied to the forward link, with either OFDM or MC-CDMA for the reverse link. The air interface parameters for B-VHF are provided in table 3.7-3.

Table 3.7-3: B-VHF Air Interface Parameters

Items	Description
Duplexing scheme	FDD or TDD (TBD within B-VHF project).
Multiple-access scheme	Forward link: MC-CDMA with additional FDMA component. Reverse Link: MC-CDMA or OFDMA.
Modulation types	BPSK, QPSK and QAM, adjustable to channel conditions.
FEC Coding	Separate FEC schemes (convolutional and turbo coding) for each service type (voice, different data service classes) according to QoS requirements. Details on FEC schemes TBD within the B-VHF project.
Diversity techniques	Yes, inherent frequency diversity due to spread-spectrum transmission based on multi-carrier technology. In addition, spatial diversity due to distributed antennas at different physical locations within a B-VHF cell.
System bandwidth	Between 500kHz and 2 MHz (TBD within the B-VHF project) resulting in a B-VHF system capacity between 1 Mbps and 3 Mbps per MHz bandwidth.
Supported data rates per user	5 kbps suitable for 4.8 kbps vocoder and multiples of 5 kbps up to the maximum B-VHF system capacity by aggregation of logical channels. Smaller data rates for management and control purposes are foreseen as well.
Max. number of simultaneously supported users per sector/cell	For ATC voice communications one party-line channel without capacity limitation is established per user group (ATC sector). Altogether up to 128 dedicated/party-line/broadcast voice channels per cell are supported. For data communications up to 256 users per cell are supported. For data/voice broadcast services an unlimited number of users is supported.
Advanced Technologies	Advanced signal processing technologies, like space-time coding, beam-forming or sophisticated receiver structures (e.g. multi-user detector), are applicable to all digital communications technologies, especially to B-VHF. Note: Tx beamforming is not applicable to broadcast data, party line and broadcast voice services.
Remarks	B-VHF is based on the multi-carrier technology (OFDM) and, therefore, highly flexible with respect to exchanging data rate per user and user capacity. Moreover, the multi-carrier technology enables to realize B-VHF as an overlay system in the VHF band, since frequency gaps can be easily utilized without interfering with existing legacy VHF systems, like for example DSB-AM or VDL. MC-CDMA radios transmit at much lower power levels compared to narrow band radios. While narrow band radios need a minimum SNR of approximately +12 dB , a wideband radio operates at much lower SNR/SIR levels determined by the spreading factor. Using advanced FEC techniques for all data services will increase system capacity and/or allow further reduction of the transmission power.

3.7.3.3 UAT Description

UAT was designed specifically for ADS-B applications, with simplicity and robustness as the design objectives. UAT operates on a single common wideband channel, providing a one Mbps channel rate. It is capable of supporting multiple broadcast applications. The UAT air interface is a binary FM modulation on a wideband channel in the DME band. A one second frame is defined, with a segment for ground broadcasts, and another segment for aircraft reports. Figure 3.7-1 shows the UAT frame structure.

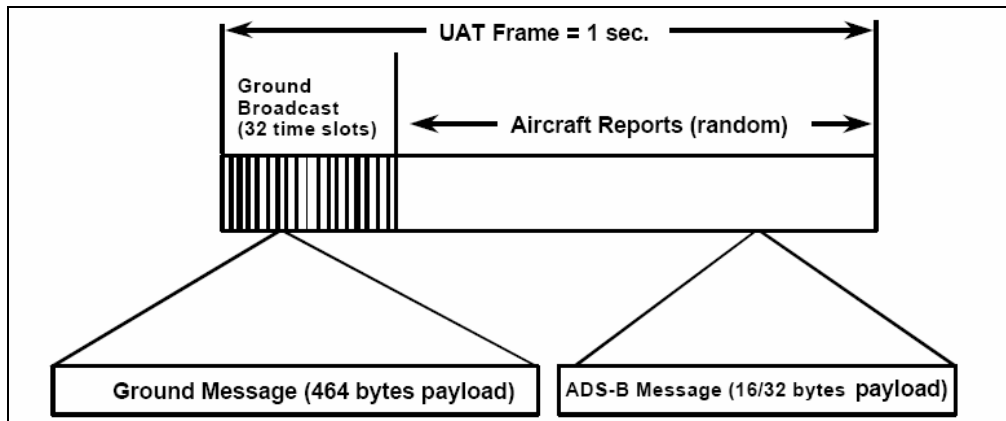


Figure 3.7-1: UAT Frame Structure

Aircraft UAT transmitters transmit one message every second, on one of 3200 message start opportunities. The messages are short bursts consisting of a 36 bit sync-sequence, either a 144 or a 272 bit payload section, and FEC parity bits. Figure 3.7-2 shows the message start opportunities of a UAT frame.

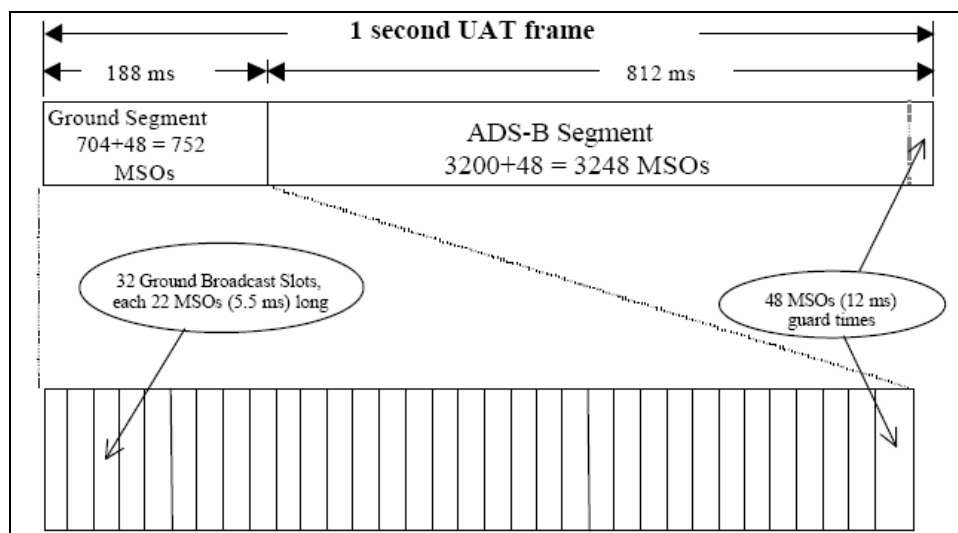


Figure 3.7-2: UAT Frame Structure Detail, Showing Message Start Opportunities

Table 3.7-4 provides some pertinent details of the UAT air interface.

Table 3.7-4: UAT Air Interface Description

Item	Description
Frequency Band	DME Band
Bit Rate	1.041667 Megabits/sec
Modulation	Binary CPFSK \pm 312 KHz
Synchronization	First 36 bits
Message Length	240 bits, short 384 bits, long
Parity	96 for the Basic ADS-B burst 112 for the Long ADS-B burst.
Address	25 bits

The UAT services provided include ADS-B (Automatic Dependent Surveillance-Broadcast), TIS-B (Traffic Information Services-Broadcast) and FIS-B (Flight Information Services-Broadcast).

3.7.3.4 Mode-S Description

Mode S is a multi-functional surveillance and communications system that was originally developed as a surveillance improvement for Mode A/C secondary surveillance radar. A data link capability was incorporated into the original design. Mode S provides an improvement over Mode A and Mode C secondary surveillance radars, in that it provides an addressed interrogation, which eliminates garbled synchronous replies. Mode S interrogations are at 1030 MHz, with replies at 1090 MHz. Figure 3.7-3 shows the Mode S Interrogation waveform. Figure 3.7-4 shows the Mode S reply waveform.

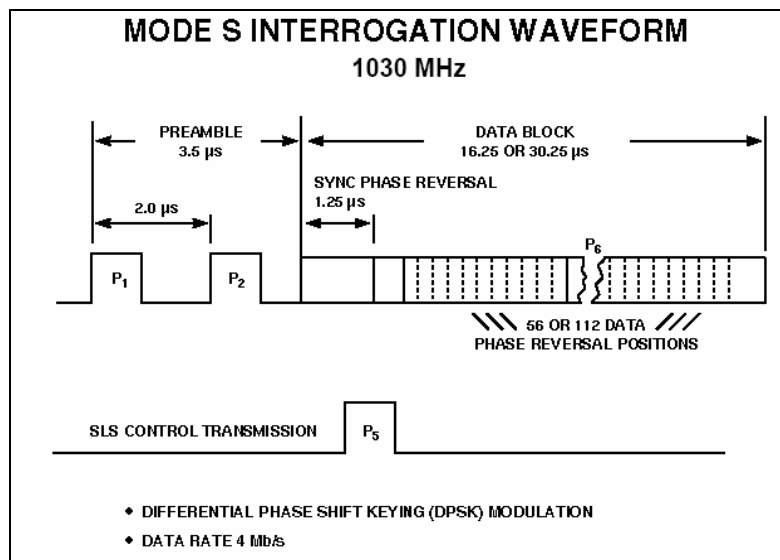


Figure 3.7-3: Mode S Interrogation Waveform⁹⁹

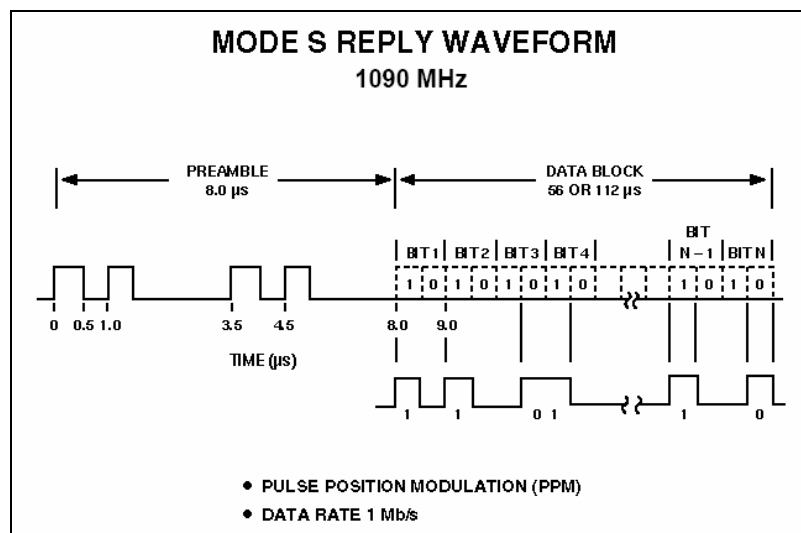


Figure 3.7-4: Mode S Reply Waveform¹⁰⁰

The typical Mode S squitter provides a control word, the Mode S address, and parity in a 56 bit format that is squittered (transmitted) once per second. Mode S Extended squitter lengthens the Mode S squitter from 56 bits to 112 bits, providing a payload capability for ADS-B (or other) messages. Figure 3.7-5 shows the Mode S Extended squitter message format, the ADS-B messages, the defined message fields, and the defined message update rates.

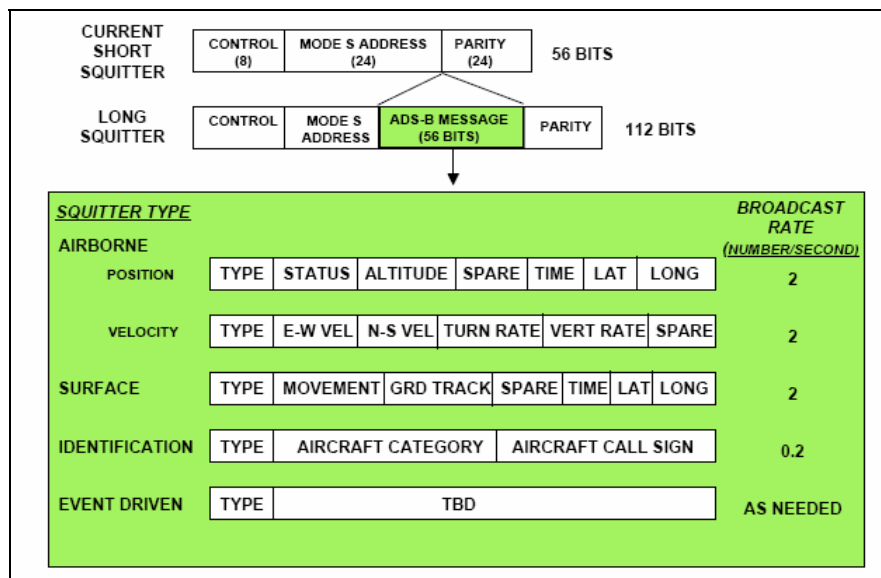


Figure 3.7-5: Mode S Extended Squitter Message Format,¹⁰¹
(Showing ADS-B Message Types, Fields, and Broadcast Rates)

Mode S air interface parameters are provided in table 3.7-5.

Table 3.7-5: Mode S Air Interface Description

Item	Description
Frequency Band	1090 MHz
Bit Rate	1 Megabit/sec
Modulation	PPM
Synchronization	4 pulse preamble (9 pulse processing)
Message Length	112 bits
Parity	24 bits
Address	24 bits

The Mode S extended squitter development is shown in figure 3.7-6.

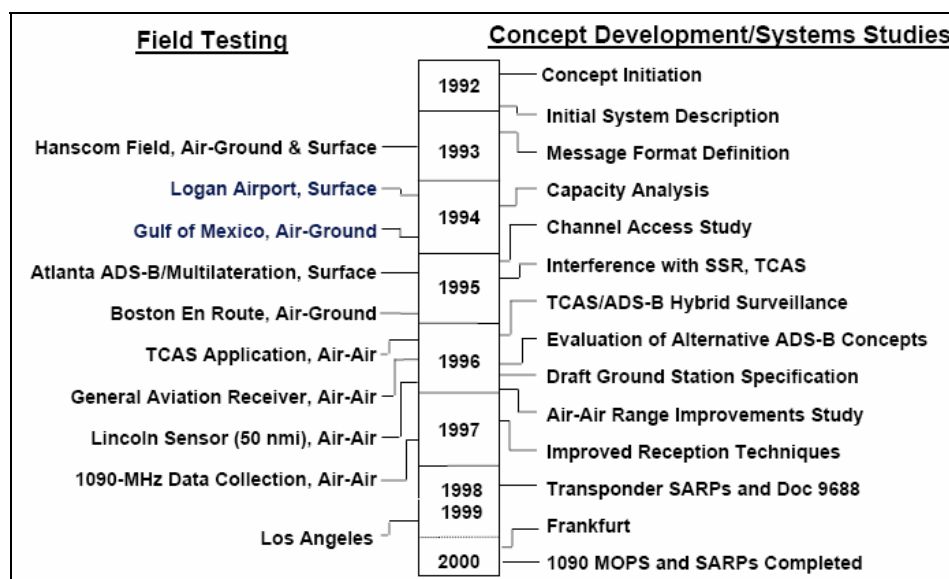


Figure 3.7-6: Mode S Extended Squitter Development¹⁰²

Extended squitter applications include air-air and air ground broadcast and addressed data transport.

3.7.4 *Concept of Use: Application to Aeronautical A/G Communications*

In this section, the application of ADL, B-VHF, UAT and Mode S Extended Squitter to aeronautical A/G communications will be discussed.

3.7.4.1 *ADL Concept of Use*

The use of ADL for ATS and AOC communications is described in this section. As was provided for other technologies, the discussion will provide the applicable frequency band, applicable airspace environments, aeronautical communications services provided, ADL services utilized, and architecture integration. These elements are presented in table 3.7-6.

Table 3.7-6: ADL Concept of Use Elements

Element	Proposed Value
Applicable Frequency Band	MLS Band (5 GHz)
Applicable Airspace Environments	Surface
Aeronautical Communications Services Provided	<ul style="list-style-type: none"> • Pilot-Controller Voice: group conference, addressed, and broadcast • A/G and G/A addressed data • G/A broadcast data
Applicable ADL Services	Packet Data Services
Architecture Integration	Requires tower voice switch integration with a VoIP server, and data network integration with FAA data networks, radios and C-Band antenna installations

3.7.4.2 *B-VHF Concept of Use*

The use of B-VHF for ATS and AOC communications is described in this section. The discussion provides the applicable frequency band, applicable airspace environments, aeronautical communications services provided, B-VHF services utilized, and architecture integration. These elements are presented in table 3.7-7.

Table 3.7-7: B-VHF Concept of Use Elements

Element	Proposed Value
Applicable Frequency Band	DME Band (960 to 1024 MHz)
Applicable Airspace Environments	Surface, Terminal, and En-route for all services, Oceanic and Polar for direct air-air services
Aeronautical Communications Services Provided	<ul style="list-style-type: none"> • Pilot-Controller Voice: group conference, addressed, and broadcast • A/G and G/A addressed data • G/A broadcast data • Direct A/A communications
Applicable B-VHF Services	All
Architecture Integration	<p>B VHF system will be able to re-use parts of existing ground infrastructure, but parts of the ground architecture will have to be added and the others upgraded in order to benefit from the new features.</p> <p>B VHF system architecture comprises a Ground Station Controller (GSC) with access to both voice- and data networks. The latter will also be used for system-internal communications between GSCs.</p> <p>The B-VHF system will have clearly defined interfaces towards the Voice Communications Systems (VCS) and existing data systems (e.g. FDPS) and networks (ATN). Limited VCS modifications may be (optionally-) required due to the increased operational capability (advanced voice functions, talker identification, urgency access, and pre-emption).</p> <p>Automated support for handoffs requires an interface towards the FDPS that must be defined yet.</p>

3.7.4.3 UAT Concept of Use

The use of UAT for ATS communications is described in this section. The discussion provides the applicable frequency band, applicable airspace environments, aeronautical communications services provided, UAT services utilized, and architecture integration. These elements are presented in table 3.7-8.

Table 3.7-8: UAT Concept of Use Elements

Element	Proposed Value
Applicable Frequency Band	DME Band (960 to 1024 MHz)
Applicable Airspace Environments	All
Aeronautical Communications Services Provided	A/G Broadcast Data Direct A/A communications
Applicable UAT Services	Broadcast data
Architecture Integration	Requires integration with FAA systems to provision FIS-B and TIS-B.

3.7.4.4 Mode S Extended Squitter Concept of Use

The use of Mode S Extended Squitter for ATS communications is described in this section. The discussion provides the applicable frequency band, applicable airspace environments, aeronautical communications services provided, Mode S Extended Squitter services utilized, and architecture integration. These elements are presented in table 3.7-9.

Table 3.7-9: Mode S Extended Squitter Concept of Use Elements

Element	Proposed Value
Applicable Frequency Band	DME Band (1030 and 1090 MHz)
Applicable Airspace Environments	All
Aeronautical Communications Services Provided	A/G Broadcast Data Direct A/A communications
Applicable B-VHF Services	Broadcast data
Architecture Integration	Requires integration with FAA systems to provision FIS-B and TIS-B.

3.7.5 Evaluation Summary and Scores

Table 3.7-10 provides the scoring summary for ADL. The rationale for the assigned scores is provided in table 3.7-11.

Table 3.7-10: ADL Evaluation Worksheet

	Criteria	Surface	Terminal	En Route	Oceanic	Polar
Voice Needs	1					
Pilot-Controller Talk Group	1A1					
Pilot-Controller Selective Addressing	1A2					
Direct Pilot-Pilot	1A3					
Broadcast capability	1A4					
Capacity provided	1B1					
Address space	1B3					
Aircraft mobility management	1C1					
Latency	1C2					
Basic Data Needs	2					
A/G and G/A Addressed Data Transport	2A1					
Ground-to-Air Broadcast Data Transport	2A2					
Aggregate Data Rate	2B1					
Number of Users	2B2					
Uplink and Downlink Priority Levels / QoS	2C1					
Latency	2C2					
Enhanced Data	3					
ADS-B	3A1					
Pilot-Pilot Data Transport	3A2					
Aggregate Data Rate	3B1					
Technology Readiness Level	4					
Standardization Status	5					
Certifiability	6					
Ground Infrastructure Cost	7					
Cost to Aircraft	8					
Spectrum Protection	10					
Security	11					
Transition	12					

Table 3.7-11: ADL Scoring Rationale

Element	Score	Rationale
Pilot-Controller Talk Group	Green (S) Red (Elsewhere)	Should support streaming media; group conference calls supported via SIP/VoIP
Pilot-Controller Selective Addressing	Green (S) Red (Elsewhere)	Should support streaming media; selective address calls supported via SIP/VoIP
Direct Pilot-Pilot	Yellow (S) Red (Elsewhere)	Pilot-pilot voice would be provided via an intermediary
Broadcast capability	Green (S) Red (Elsewhere)	Broadcast via layer 2 broadcast address and IP multicast
Capacity provided	Green (S) Red (Elsewhere)	8 MHz of spectrum could support large number of talk groups and other voice channels. However, as no capacity increase can be provided in other regions, only the surface merited a green.
Address space	Green	Supports thousands of users
Aircraft mobility management	Green (S) Red (Elsewhere)	Should support mobility between multiple cells on an airport surface
Latency	Yellow	Should support QoS so that calls should be set up in timely fashion with low latency, but perhaps not at the level required for voice
A/G and G/A Addressed Data Transport	Green (S) Red (Elsewhere)	Network layers are not specified. Assuming IP, this is provided via mobile IP
Ground-to-Air Broadcast Data Transport	Green (S) Red (Elsewhere)	Broadcast via layer 2 broadcast address and IP multicast
Aggregate Data Rate	Green	Provides many Mbps in available bandwidth
Number of Users	Green	Supports thousands of users
Uplink and Downlink Priority Levels/QoS	Green	Should support QoS
Latency	Green	Should support QoS; ADL has sufficient bandwidth to deliver high priority data quickly
ADS-B	Red	Direct mode without intermediary was not envisioned. Since forward link and reverse link were to be different, this can not be provided. However, individual position reporting, and ground FIS-B reporting would be provided.
Pilot-Pilot Data Transport	Yellow (S) Red (Elsewhere)	Pilot-pilot data would be provided via an intermediary
Aggregate Data Rate	Green	Should support multiple Mbps data rate
Technology Readiness Level	Red	System has been demonstrated on an airport surface, but only the forward link.
Standardization Status	Red	No standards exist
Certiability	Yellow	Was being developed specifically for aviation needs
Ground Infrastructure Cost	Yellow	Custom equipment, as compared to 802.16. Have to assume that the cost will be higher than 802.16.
Cost to Aircraft	Green	Cost of avionics should be relatively low.
Spectrum Protection	Yellow	Fits into the MLS or DME spectral band
Security	Green	ADL provides authentication and integrity.
Transition	Green	Supports incremental deployment and operational transparency

Table

Table 3.7-12 provides the scoring summary for B-VHF. The rationale for the assigned scores is provided in table 3.7-13.

Table 3.7-12: B-VHF Evaluation Worksheet

	Criteria	Surface	Terminal	En Route	Oceanic	Polar
Voice Needs	1					
Pilot-Controller Talk Group	1A1					
Pilot-Controller Selective Addressing	1A2					
Direct Pilot-Pilot	1A3					
Broadcast capability	1A4					
Capacity provided	1B1					
Address space	1B3					
Aircraft mobility management	1C1					
Latency	1C2					
Basic Data Needs	2					
A/G and G/A Addressed Data Transport	2A1					
Ground-to-Air Broadcast Data Transport	2A2					
Aggregate Data Rate	2B1					
Number of Users	2B2					
Uplink and Downlink Priority Levels / QoS	2C1					
Latency	2C2					
Enhanced Data	3					
ADS-B	3A1					
Pilot-Pilot Data Transport	3A2					
Aggregate Data Rate	3B1					
Technology Readiness Level	4					
Standardization Status	5					
Certifiability	6					
Ground Infrastructure Cost	7					
Cost to Aircraft	8					
Spectrum Protection	10					
Security	11					
Transition	12					

Table 3.7-13: B-VHF Scoring Rationale

Element	Score	Rationale
Pilot-Controller Talk Group	Green (S, T, and E) Red (O and P)	The B-VHF support for voice services will include Controller-Pilot party line service. In particular, Controller-Pilot party line service will be supported by directly implementing features of legacy voice system (like wide-area coverage, CLIMAX, sector coupling with re-transmission) or providing functional equivalents that are transparent to the controller and pilots. B-VHF requirement # FR-FRQ-V-02 (from "Report on Applications Communications Requirements," Report # D-05)
Pilot-Controller Selective Addressing	Green (S, T, and E) Red (O and P)	The B-VHF support for voice services will include selective voice service. B-VHF requirement # FR-FRQ-V-14, V-17
Direct Pilot-Pilot	Green (all domains)	The B-VHF support for voice services will include pilot-pilot voice service. B-VHF requirement # FR-FRQ-V-03
Broadcast capability	Green (S, T, and E) Red (O and P)	The B-VHF support for voice services will include broadcast voice (uplink broadcast only).
Capacity provided	Green (all domains)	B-VHF provides system capacity to cover voice and data traffic demands well beyond 2020, based on the capacity requirements specified in the MACONDO study. The system will provide increased capacity and spectral efficiency as compared to 25 kHz DSB-AM.
Address space	Green (all domains)	The B-VHF system has no user capacity limitation (will not impose any constraints to the maximum number of airborne users per User Group/sector). B-VHF requirement # FR-FRQ-V-06
Aircraft mobility management	Green (S, T, and E) Red (O and P)	The B VHF system is based on cells with system-internal handoff between cells. This hand-over is fully transparent to the users (pilots, airline dispatchers and controllers). The system itself internally manages aircraft mobility at the sub-network level, providing support for semi-automated or—if allowed by the Operational Concept—even fully-automated handoff between ATC sectors/User groups. B-VHF requirement # FR-FRQ-V-15, 07
Latency	Green (all domains)	Latency will be less than 250 ms.
A/G and G/A Addressed Data Transport	Green (S, T, and E) Red (O and P)	B-VHF system design supports directly. B-VHF requirement # FR-FRQ-G-32
Ground-to-Air Broadcast Data Transport	Green (S, T, and E) Red (O and P)	B-VHF system design supports directly. B-VHF requirement # FR-FRQ-G-32
Aggregate Data Rate	Green (all domains)	The B VHF system data link capacity is sufficient to cover a mixture of voice and data link services under realistic loading by 2015 and beyond (MACONDO PIAC figures for 2015 have been extrapolated to 2020 by using realistic traffic growth hypotheses). The scenarios of data link usage represent realistic mix of different data link services with varying instantaneous/peak throughput, as well as very different delay requirements. B-VHF requirement # FR-FRQ-D-06
Number of Users	Green (all domains)	B-VHF requirement # FR-FRQ-D-01
Uplink and Downlink Priority Levels/QoS	Green (all domains)	The system is being designed by taking into account required non-functional requirements (QoS, in particular end-to-end message latency, data integrity and throughput). B-VHF requirement # FR-FRQ-D-03
Latency	Green (all domains)	The system is being designed by taking into account required non-functional requirements (QoS, in particular end-to-end message latency, data integrity and throughput). B-VHF requirement # FR-FRQ-D-07
ADS-B	Yellow (all domains)	Not currently part of the design concept

Element	Score	Rationale
Pilot-Pilot Data Transport	Green (all domains)	The support for A/A communications in areas where Ground Stations are deployed is indirect, by using ground station as a relay. In remote areas without ground support, a direct mode is provided. B-VHF requirement # FR-FRQ-G-32
Aggregate Data Rate	Green (all domains)	B-VHF requirement # FR-FRQ-G-39
Technology Readiness Level	Red	The B-VHF project has rated themselves as a TRL 3 (TRL 3 and below merit a red). The following is a quote from the B-VHF project: "TRL 3 will be achieved during B-VHF project, due December 2005. TRL 4 will be achieved during B-VHF project, due June 2006"
Standardization Status	Red	Physical layer is common with proposed 4th generation technologies, which are not yet standardized. No aviation standards exist. The B VHF system design will re-use parts of already standardized communications solutions. AMBE 4.8 kbps vocoder will be used for all B VHF voice purposes. Other re-use examples include-, but are not limited to, VDL Mode 3 physical frame structure and management channel concept.
Certifiability	Yellow	Being designed for safety-related service
Ground Infrastructure Cost	Yellow	System will be able to re-use parts of existing ground infrastructure, but parts of the ground architecture will have to be added and the others upgraded in order to benefit from the new features. B VHF system architecture comprises a Ground Station Controller (GSC) with access to both voice- and data networks. Voice switch modifications may be required due to advanced voice functions, such as talker identification, urgency access, and pre-emption. Automated support for handoffs requires an interface that must be defined yet.
Cost to Aircraft	Green	The intention of the B VHF concept is to require minimum changes in the airborne architecture. Airborne B VHF radio standard would remain backward-compatible with DSB-AM and VDL Mode 2 modes of operation, the compatibility would encompass the interface compatibility for voice access (some new signaling features would have to be added). Inclusion of B-VHF technology as an ATN sub-network requires limited modifications of the airborne CMU (it would have to host higher layers of the B-VHF sub-network protocol stack). Avionics cost is likely comparable to VDL 3
Spectrum Protection	Green	System proponents are targeting VHF band, but are investigating system use at other frequencies.
Security	Green	B-VHF provides authentication and integrity (requirement # FR-FRQ-G-30).
Transition	Green	System will support incremental transition.

Table 3.7-14 provides the scoring summary for UAT. The rationale for the assigned scores is provided in table 3.7-15.

Table 3.7-14: UAT Evaluation Worksheet

	Criteria	Surface	Terminal	En Route	Oceanic	Polar
Voice Needs	1					
Pilot-Controller Talk Group	1A1					
Pilot-Controller Selective Addressing	1A2					
Direct Pilot-Pilot	1A3					
Broadcast capability	1A4					
Capacity provided	1B1					
Address space	1B3					
Aircraft mobility management	1C1					
Latency	1C2					
Basic Data Needs	2					
A/G and G/A Addressed Data Transport	2A1					
Ground-to-Air Broadcast Data Transport	2A2					
Aggregate Data Rate	2B1					
Number of Users	2B2					
Uplink and Downlink Priority Levels / QoS	2C1					
Latency	2C2					
Enhanced Data	3					
ADS-B	3A1					
Pilot-Pilot Data Transport	3A2					
Aggregate Data Rate	3B1					
Technology Readiness Level	4					
Standardization Status	5					
Certifiability	6					
Ground Infrastructure Cost	7					
Cost to Aircraft	8					
Spectrum Protection	10					
Security	11					
Transition	12					

Table 3.7-15: UAT Scoring Rationale

Element	Score	Rationale
Pilot-Controller Talk Group	Red (all domains)	UAT has no QoS provisions, and MAC is simple slotted random access. Further, actual user data rate is quite low. Voice can not be supported.
Pilot-Controller Selective Addressing	Red (all domains)	UAT has no QoS provisions, and MAC is simple slotted random access. Further, actual user data rate is quite low. Voice can not be supported.
Direct Pilot-Pilot	Red (all domains)	UAT has no QoS provisions, and MAC is simple slotted random access. Further, actual user data rate is quite low. Voice can not be supported.
Broadcast capability	Red (all domains)	UAT has no QoS provisions, and MAC is simple slotted random access. Further, actual user data rate is quite low. Voice can not be supported.
Capacity provided	Red (all domains)	UAT has no QoS provisions, and MAC is simple slotted random access. Further, actual user data rate is quite low. Voice can not be supported.
Address space	Red (all domains)	UAT has no QoS provisions, and MAC is simple slotted random access. Further, actual user data rate is quite low. Voice can not be supported.
Aircraft mobility management	Red (all domains)	UAT has no QoS provisions, and MAC is simple slotted random access. Further, actual user data rate is quite low. Voice can not be supported.
Latency	Red (all domains)	UAT has no QoS provisions, and MAC is simple slotted random access. Further, actual user data rate is quite low. Voice can not be supported.
A/G and G/A Addressed Data Transport	Red (all domains)	UAT does not define a mechanism for addressing packets to specific users
Ground-to-Air Broadcast Data Transport	Green (S, T, and E) Red (O and P)	Provide a G/A broadcast capability for continental airspace
Aggregate Data Rate	Green (all domains)	Provides a high data rate
Number of Users	Green (all domains)	The number of users can be quite large
Uplink and Downlink Priority Levels/QoS	Red (all domains)	QoS and prioritization is not supported
Latency	Red (all domains)	Since UAT doesn't support addressed data, it clearly can not meet the latency requirements associated with addressed data.
ADS-B	Yellow (all domains)	Designed for this function
Pilot-Pilot Data Transport	Green (all domains)	Potential modifications might enable a rudimentary air-air data capability
Aggregate Data Rate	Green (all domains)	Can meet the yellow range for enhanced data
Technology Readiness Level	Green	Technology is in use for ADS-B
Standardization Status	Green	Aviation standards exist
Certifiability	Green	No certification issues are anticipated. UAT is in the certification process.
Ground Infrastructure Cost	Green	Should be low cost, but as with any high data rate system, there is a cost associated with the ground transport of high volumes of data
Cost to Aircraft	Green	Low cost avionics exist
Spectrum Protection	Yellow	DME band
Security	Yellow	Not currently provided, but presumably A and I features could be incorporated at the application layer
Transition	Green	No known transition issues

Table 3.7-16 provides the scoring summary for Mode S Extended Squitter. The rationale for the assigned scores is provided in table 3.7-17.

Table 3.7-16: Mode S Evaluation Worksheet

	Criteria	Surface	Terminal	En Route	Oceanic	Polar
Voice Needs	1					
Pilot-Controller Talk Group	1A1					
Pilot-Controller Selective Addressing	1A2					
Direct Pilot-Pilot	1A3					
Broadcast capability	1A4					
Capacity provided	1B1					
Address space	1B3					
Aircraft mobility management	1C1					
Latency	1C2					
Basic Data Needs	2					
A/G and G/A Addressed Data Transport	2A1					
Ground-to-Air Broadcast Data Transport	2A2					
Aggregate Data Rate	2B1					
Number of Users	2B2					
Uplink and Downlink Priority Levels / QoS	2C1					
Latency	2C2					
Enhanced Data	3					
ADS-B	3A1					
Pilot-Pilot Data Transport	3A2					
Aggregate Data Rate	3B1					
Technology Readiness Level	4					
Standardization Status	5					
Certifiability	6					
Ground Infrastructure Cost	7					
Cost to Aircraft	8					
Spectrum Protection	10					
Security	11					
Transition	12					

Table 3.7-17: Mode S Extended Squitter Scoring Rationale

Element	Score	Rationale
Pilot-Controller Talk Group	Red (all domains)	Mode S Extended Squitter has no QoS provisions, and MAC is simple random access. Further, actual user data rate is quite low. Voice can not be supported.
Pilot-Controller Selective Addressing	Red (all domains)	Mode S Extended Squitter has no QoS provisions, and MAC is simple random access. Further, actual user data rate is quite low. Voice can not be supported.
Direct Pilot-Pilot	Red (all domains)	Mode S Extended Squitter has no QoS provisions, and MAC is simple random access. Further, actual user data rate is quite low. Voice can not be supported.
Broadcast capability	Red (all domains)	Mode S Extended Squitter has no QoS provisions, and MAC is simple random access. Further, actual user data rate is quite low. Voice can not be supported.
Capacity provided	Red (all domains)	Mode S Extended Squitter has no QoS provisions, and MAC is simple random access. Further, actual user data rate is quite low. Voice can not be supported.
Address space	Red (all domains)	Mode S Extended Squitter has no QoS provisions, and MAC is simple random access. Further, actual user data rate is quite low. Voice can not be supported.
Aircraft mobility management	Red (all domains)	Mode S Extended Squitter has no QoS provisions, and MAC is simple random access. Further, actual user data rate is quite low. Voice can not be supported.
Latency	Red (all domains)	Mode S Extended Squitter has no QoS provisions, and MAC is simple random access. Further, actual user data rate is quite low. Voice can not be supported.
A/G and G/A Addressed Data Transport	Green (S, T, and E) Red (O and P)	Can support this if the message set is defined.
Ground-to-Air Broadcast Data Transport	Green (S, T, and E) Red (O and P)	Provide a G/A broadcast capability for continental airspace
Aggregate Data Rate	Green (all domains)	Provides a high data rate
Number of Users	Green (all domains)	The number of users can be quite large
Uplink and Downlink Priority Levels/QoS	Red (all domains)	QoS and prioritization is not supported
Latency	Red (all domains)	Depends on numbers of aircraft. In the worst case, delay targets wont be met, due to system self interference.
ADS-B	Green (all domains)	Provides this function as a native capability
Pilot-Pilot Data Transport	Green (all domains)	Provides this function as a native capability
Aggregate Data Rate	Yellow (all domains)	Can meet the yellow range for enhanced data
Technology Readiness Level	Green	Technology is in use
Standardization Status	Green	Aviation standards exist
Certifiability	Green	Mode S Extended Squitter has been certified
Ground Infrastructure Cost	Red	High cost infrastructure
Cost to Aircraft	Red	High cost infrastructure
Spectrum Protection	Yellow	DME band
Security	Yellow	Not currently provided, but presumably A and I features could be incorporated at the application layer
Transition	Green	No known transition issues

3.7.5.1 Summary

The B-VHF candidate scores well across a broad range of criteria. However, it is important to realize that it is an immature system in an early stage of development. B-VHF is being developed by a consortium of limited membership. If the B-VHF development cannot be brought into the open as part of a global international standardization effort, the solution set should be augmented with such an open standardization approach.

ADL scores well as a surface solution, but not as highly as 802.16, which was evaluated in an earlier section. It does have a design goal of providing data link to fast moving aircraft, which may discriminate it from the more limited mobility of 802.16e. Should the analysis of 802.16 indicate an inability to provide data line at reasonable rates during takeoff and landing, then the investigation of a custom solution for the airport surface might prove fruitful.

UAT scores well only for expanded data, and then primarily for its ability to support ADS-B for which it was designed. It provides no QoS so its support for basic data is very limited. It also has no ability at all to support voice.

Mode S Extended Squitter scores well for enhanced data applications.

3.8 Military Communications

3.8.1 Overview of the Family

The challenge of assuring that the future's Air Traffic Services (ATS) communications needs are addressed effectively and efficiently requires that all potential sources of communications technologies be investigated and evaluated as appropriate.

The Military Services employ a variety of communication technologies for command and control (C2), situational awareness (SA) and Air Control (AC). At an overarching functional level, military C2 and SA are analogous to the ATS Operational Applications Categories:

- Pilot-Controller Dialog
- Pilot-Pilot Dialog
- Flight Information Exchanges
- Air Traffic Management (ATM) Exchanges
- Information Downlink
- Air-Air Surveillance.

In this context, Military communications were reviewed to identify potential candidates that may support future ATS communications needs. The review process looked at technologies that could potentially perform one or more of the Operational Applications Categories, that could potentially support the number of ATS participants, and that operate in the VHF and UHF frequency bands. For clarification, the term "communications technologies" used here refers to a communications system/waveform not to specific hardware/software ensembles. This review identified the following communications technologies.

3.8.1.1 *SINCGARS (Single-Channel Ground and Airborne Radio System)*

Background. This is a mature tactical communications system. Development commenced in the 1970s and production commenced in 1987. Since, the system has undergone continuous improvement. In 1989, secure voice and key data capabilities were added. In 1996, GPS interface and packet communications capabilities were added. In 1998, the radio underwent a 50% weight reduction, and added features to improve communications reliability and significantly increase battery life.

Description. SINCGARS is a 2320 25 kHz channel frequency hopped, VHF, 30 to 88 MHz secure voice and data system. The system also provides in-the-clear single channel (frequency) communications. The system provides the primary anti-jam (AJ), limited probability-of-intercept (LPI) C2 surface-to-surface and surface-to-air connectivity for a Division (Army or Marine Corps). In addition, the Air Force and Navy employ the system to support Army, Marine and Joint operations. The system is installed on

personnel, vehicles (wheel and track), helicopters, planes and ships. Data communications support SA and messages are in Variable Message Format (VMF). Communications are line-of-sight (LOS) with relay and variable power.

3.8.1.2 *Link 16.*

Background. Link 16 is a North Atlantic Treaty Organization (NATO) term for a message standard and waveforms that support distribution of anti-jam, secure data and voice. This is a mature tactical communications system. Development commenced in the 1970s and the first terminals [Joint Tactical Information Distribution System (JTIDS) Class 1 terminals weighing 600 lbs were installed on Air Force E-3 AWACS aircraft and in Air Operations Centers (AOCs) in 1979 to support NATO airspace SA. JTIDS Class 2 Terminals, 150 lbs, were developed in the 1980s and entered service on Navy ships and planes in 1994 to support air defense. MIDS (Multi-functional Information Distribution System) Low Volume Terminals (LVTs), 60 lbs, were developed in the 1990s by a group of NATO nations. Currently, the terminals are in production and being installed on aircraft and ships, and in facilities. In the late 1990s, in response to the need to disseminate Link 16 messages within a large geographic area of operations, Joint Range Extension (JRE) was developed and specified with a JRE Application Protocol (JREAP). JREAP is a standard for encapsulating Link 16 messages for transmission over long-haul media, including land lines, IP networks and Satellite Communications.

Description. This is a UHF, frequency hopping, 51 frequencies, over 960 to 1215 MHz Tactical Data Link (TDL) system. The system provides air-to-air and air-to-surface AJ secure voice and data communications. Data communications are via the MIL-STD-6016 J-series message set. The system is installed and integrated on ships, planes and in facilities. The primary mission of the system is to provide SA and C2 for air and missile defense and digital data and voice control of tactical aircraft. Communications are LOS with relay and variable power. In addition, Joint Range Extension (JRE) provides a ship or facility based capability for global Link-16 connectivity via satellite or cable Internet communications. Note that there are strict operational restrictions on Link 16 operation due to incompatibilities with DME and the air traffic control radio beacon system (ATCRBS).

3.8.1.3 *HAVEQUICK*

Background. HAVEQUICK is a mature tactical communications system. Development commenced in the early 1970s, and in beginning in the late 1970s radios were installed on F-15, F-16 and AWACS aircraft to provide AJ C2 and SA voice communications. Over the next 25 years the technology was continuously improved and over 60,000 radios have seen service in a variety of military platforms. In addition, a data communications capability was developed and fielded. Currently, HAVEQUICK is the primary provider of the military services' secure air-to-air AJ voice communications.

Description. This is a 7000 25 kHz channel frequency hopped, VHF, 225 to 400 MHz secure voice and data system. The system provides the primary anti-jam air-to-air connectivity for tactical air operations. The system also provides in-the-clear single channel (frequency) communications. The system is installed on Air Force, Navy and Army planes and helicopters, as well as in facilities and on ships. Data communications are accomplished with a modem to support situation awareness and messages are in Variable Message Format (VMF). Communications are line-of-sight (LOS) with variable power. Note that in peacetime, HaveQuick only uses a very limited number of the 7000 channels (~20), but the full hopping is used in wartime mode.

3.8.1.4 *EPLRS/SADL (Enhanced Position Location Reporting System/Situation Awareness Data Link)*

Background. EPLRS/SADL is a mature tactical communications system. EPLRS is a Pre-Planned Program Improvement (P3I) of PLRS. PLRS development commenced in the 1970s was fielded in the 1980s. EPLRS was initially fielded with the Army's 1st Cavalry Division and is now fielded throughout

the Army and the Marine Corps. In the late 1990s, the Air National Guard (ANG) began to equip their F-16 aircraft with SADL and currently, all ANG F-16s employ SADL for the close air support mission.

Description. EPLRS/SADL is a frequency hopped, VHF, 420 to 450 MHz secure data system. Communications are surface-to-surface and surface-to-air. EPLRS provides SA for Army, Marine and amphibious operations, and is the Army's tactical internet backbone. The system is installed on vehicles (wheel and track), helicopters, planes, and ships and in facilities. SADL installs the system on attack aircraft providing air-to-air and air-to ground connectivity for coordinated tactical air support operations with EPLRS equipped forces on the ground.

3.8.1.5 JTRS (Joint Tactical Radio System)

Background. Since the 1970s there have been research and development efforts focused on the realization programmable waveform radios. First, there was Integrated Communications Navigation and Identification Avionics (ICNIA) that featured one of the first uses of a Digital Signal Processor (DSP) based programmable modem. This was followed by the SPEAKeasy program in the 1990s that developed a software radio core with an ad-hoc RF front-end. From this effort, a Programmable Modular Communications System Integrated Product Team (IPT) was initiated in 1997. The IPT developed the technical baseline for the JTRS program, which commenced in 2001.

Description. This is an in-development program to develop a new family of programmable waveform radios for the military services. The radios will support existing waveforms including SINCGARS, Link-16, HAVEQUICK and EPLR/SADL described above, the Air Traffic Control VHF waveforms (AM Voice, VDL Mode-2 and Mode-3) and new waveforms to support the military's transformation to Net-Centric Operations. This new family of radios will support special operations personnel, installations in aircraft, ships, helicopters, vehicles (wheel and track) and facilities.

3.8.1.6 Military Technology for Civil Applications

The fundamental issue with the transfer of Military Technology to the civil sector is security. To illustrate, all of the technologies discussed above employ encryption for frequency hopping. In addition, data is also encrypted. Further, the specific performance characteristics of the systems are not available to the civil sector. Notice, secure reliable communications are necessary for effective military operations. Given this situation, it is still possible that the above listed technologies at some fundamental level might have application to ATS in the 118 to 137 MHz or the 960 to 1024 MHz frequency bands.

3.8.2 Selection of Evaluation Candidates via Minimum Threshold Test

Five military technologies were identified, as indicated above, as having potential to support the future's ATS communications needs. As indicated in table 3.8-1, three of these technologies were rejected. These rejected systems are also briefly discussed in the subsections immediately following.

Table 3.8-1: Rationale for Selection of Military Candidate Solutions

System	Evaluate	Rationale
Military Technologies		
JTIDS/MIDS/JRE (Link 16)	Yes	FAA Spectrum engineering indicates that the frequency hopping aspects of this waveform will likely result in mutual interference at a certain loading level (# of emitters present in a particular environment). Use of the waveform in a non-hopping mode is under consideration.
SINCGARS	Yes	This is a narrowband frequency hopper that could provide voice and data within the VHF band
EPLRS	No	This is a data only system.
HAVEQUICK	No	This is a narrowband frequency hopper and will not meet the data needs of the future aeronautical communications
JTRS	No	This is not a waveform. It was discussed here because the modular software architecture and programmable software radio aspects of JTRS are enabling technologies that are applicable to the future communications study

3.8.2.1 HAVEQUICK

This system basically performs the ATS voice communications now conducted with the current FAA approved technology. It offers no additional waveform capabilities that would increase the number channels available for ATS communications. In addition, the HAVEQUICK data communications capability is 16 kbps and is external modem dependent and has no realistic growth potential to support the Basic Data Link Needs of 31.5 kbps.

3.8.2.2 EPLRS/SADL

This system is very similar to Link 16. Like Link 16, it is Time Division Multiple Access (TDMA) and uses formatted messages (VMF) for data communications. However, it has no voice communications capabilities. In this context, it provides no potential beyond what Link 16 may afford ATS communications needs.

3.8.2.3 JTRS

As indicated above, the term “communications technologies” used here refers to a communications system/waveform not to specific hardware/software ensembles. JTRS technology is basically a hardware/software environment for communication waveforms. In addition, beyond the SINCGARS and Link 16 waveforms, no JTRS waveforms have been identified that have potential to address the ATS communications needs.

3.8.3 Technology Description

3.8.3.1 SINCGARS

The system is a family of VHF-FM radio sets as indicated in table 3.8-2 below.

Table 3.8-2 SINCGARS Radio Sets

Set Description	Service Application
AN/VRC-87 Vehicle/Tactical ground Vehicular, Short Range	A
AN/VRC-88 Vehicle/Tactical ground Vehicular, short range, dismountable	A,MC
AN/VRC-89 Vehicle/Tactical ground Vehicular, short/long range	A,MC
AN/VRC-90 Vehicle/Shipboard/Tactical ground Vehicular, long	A,MC,N
AN/VRC-91 Vehicle/Tactical ground Vehicular Short/long range, dismountable	A,MC,AF
AN/VRC-92 Vehicle/Tactical ground Vehicular, Dual long range, retransmission	A,MC
AN/PRC- 119 Tactical ground Short Range, dismount	A,MC,AF
AN/ARC-186 Airborne/Vehicle Aircraft/Vehicle mounted	A,AF
AN/ARC-201(V) Airborne SINCGARS	A
AN/ARC-210 Shipboard/Aircraft/air to ground, air to air Aircraft mounted, long range, retransmission	All services
AN/ARC-222 Aircraft/air to ground, air to air Remote mount RCV/XMT, Remote Control set Airborne (replacement for AN/ARC-186)	AF
AN/PSC- 5D Ground/Multiband SINCGARS Interoperable	All services
AN/PRC-117F Ground/Multiband SINCGARS Interoperable	All services
AN/SRC-54B Shipboard SINCGARS	N
Radio Nomenclature A=Army, MC=Marine Corps, N=Navy, AF=Air Force	

SINCGARS operates in either the single frequency [single channel (SC)] or frequency hop (FH) mode, and stores both SC frequencies and FH loadsets. System users are organized into networks with a network control station (NCS). Networks are set to a SC frequency for initial network activation. Standard operating procedures provide network users with the common frequency information to verify equipment

operation and network entry. During initial net activation, all operators in the net tune to the network entry frequency provided. After communications are established, the NCS transfers the hopping variables to the other network members and the net switches to the FH mode.

SINGARS equipment supports user participation in multiple networks. Users outside a FH network can use a hailing method to request access to the FH network. When hailing a network, a user outside the network contacts the network control station (NCS) on a designated cue frequency. In the active FH mode, the SINGARS radio gives audible and visual signals to the operator that an external subscriber wants to communicate with the FH network. The SINGARS operator must change to the cue frequency to communicate with the outside radio system. The FH information is provided to the new network participant via Electronic Remote Fill (ERF) from the network Master node.

3.8.3.1.1 SINGARS Services Provided and Key Features

The system operates on any of 2320 channels between 30 and 88 MHz with a channel separation of 25 kHz. The radios superimposes either the voice or digital inputs onto the radio frequency (RF) carrier wave. In FH mode, the carrier frequency changes about 100 times per second over portions of the 30 to 88 MHz band. The larger the number of the frequencies and wider the distribution across the band (30 to 88 MHz), the better SINGARS performs. Typically, 1200 frequency hop (FH) steps will adequately support both voice and data communications in an Army heavy division environment (approximately 3,000 radios organized into approximately 150 nets) distributed over geographic areas up to 300 x 300 km in size. These continual changes in frequency hinder enemy intercept and jamming units from locating or disrupting communications. In the SC mode, the SC frequency can be offset +/-5 or 10 kHz.

The system provides data rates up to 16,000 bits per second with forward error correction (FEC) coding. Enhanced data modes provide packet (IPv4) and RS-232 data. In addition, a GPS interface enables the radio to provide its location with each Push to Talk (PTT).

Most ground SINGARS radios have the ability to control output power; however, most airborne SINGARS radio sets are fixed power. Those RTs with power settings can vary transmission range from approximately 200 meters (660 feet) to 10 kilometers (km) (6.2 miles). Adding a power amplifier increases the line of sight (LOS) range to approximately 40 km (25 miles). The variable output power level allows users to operate on the minimum power necessary to maintain reliable communications, thus lessening the electromagnetic signature given off by their radio sets. This ability is of particular importance at major command posts, which operate in multiple networks. SINGARS is capable of retransmission (relay) in SC, FH, and combined FH and SC modes.

3.8.3.1.2 SINGARS Functional Architecture

The SINGARS functional architecture is illustrated in figure 3.8-1 below. As illustrated, SINGARS is deployed as a family of interconnected voice/data communication networks. The figure shows an Army Mechanized Infantry Division network laydown for its infantry and armor units, which reflects the chain of command structure of figure 3.8-1 the Division. In this laydown, we have SINGARS nets at the Division, Brigade (3 per Division), Battalion (nominally 3 per Brigade), and Company (3 + HQ Company per Battalion) levels. The nets are interconnected via the command structure where for example, a Company Commander has two SINGARS radios one to connect him/her to the Battalion network and one to connect him/her into their Company network. It should be noted that there are similar laydowns for the Division's artillery, cavalry, aviation and other support elements as well as the Marines and the Navy. SINGARS is a Joint communications system.

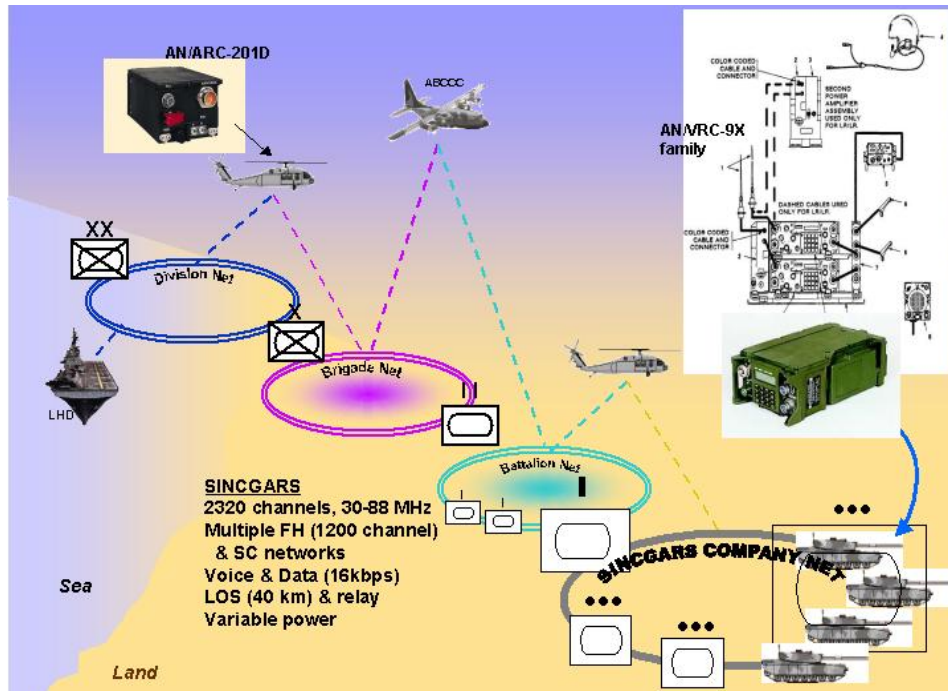


Figure 3.8-1: SINCGARS Architecture

Each network has a Network Control Station (NCS). Network Security information [frequency hop (FH) set and encryption materials] are disseminated down the chain of command Division-Brigade-Battalion-Company. The FH set for each network is generated with a common set of frequencies (approximately 1200 of the 2320 available) selected from the 30 to 88 MHz band. Each network participant brings up his/her radio using GPS as the time reference, loads the communications security materials via a fill device, and tunes to a pre-determined/issued network entry frequency and contacts the NCS [when the frequency is clear using push to talk (PTT)]. The NCSs disseminate the FH information to the network participants via Electronic Remote Fill (ERF) over this frequency [Single Channel (SC)] referred to as the cueing channel/frequency. In terms of the figure above, each tank in the Company has a radio(s) and they form a network that provides all of the participants situation awareness (SA) and the Company Commander, Executive Officer and Platoon Leaders the connectivity for real-time Command and Control (C2).

Connectivity in the Battalion and Company nets is Line-of-Sight (LOS) and up the command chain it is primarily LOS. Beyond LOS communications are supported via relay. The SINCGARS connectivity in the Division also includes radios on organic aircraft (helicopters) which operate in their own networks and participate in the Divisions line unit (Brigades, infantry, armor and artillery Battalions and Companies/Batteries) networks. In addition, Air Force Tactical Air Control Parties (TACPs) participate in the Division, Brigade and Battalion networks to coordinate close air support (CSA). In addition, at the Division, Brigade and Battalion levels connectivity to Air Borne C2 Centers (ABCCC) and Navy amphibious ships are maintained.

SINCGARS also provides data communications (plane or cipher text). The radios provide interfaces for teletype (analog) and modem (digital) data. Communications are Carrier Sense Multiple Access (CSMA) over the voice networks or via wire. Digital data is in formatted message formats with emphasis to supporting the Division's tactical fires.

In the following figure 3.8-2, a notional functional architecture of SINCGARS supporting ATS is depicted. In this architecture, SINCGARS networks are assigned to Sectors to support the ATS voice and data communications needs to be discussed in subsequent paragraphs. In particular, the graphic indicates

the assignment of 6 each SC or FH nets to Sector 119 for voice and data communications between the ground and in-sector 119 aircraft. In addition, a FH net is designated for a Sector 119 controller to pilot private channel. Access to these networks is to be via Sector established cueing frequencies. Notice, this architecture is consistent with how SINGARS operates. However, its capabilities to support ATS based on specific needs are addressed in subsequent sections.

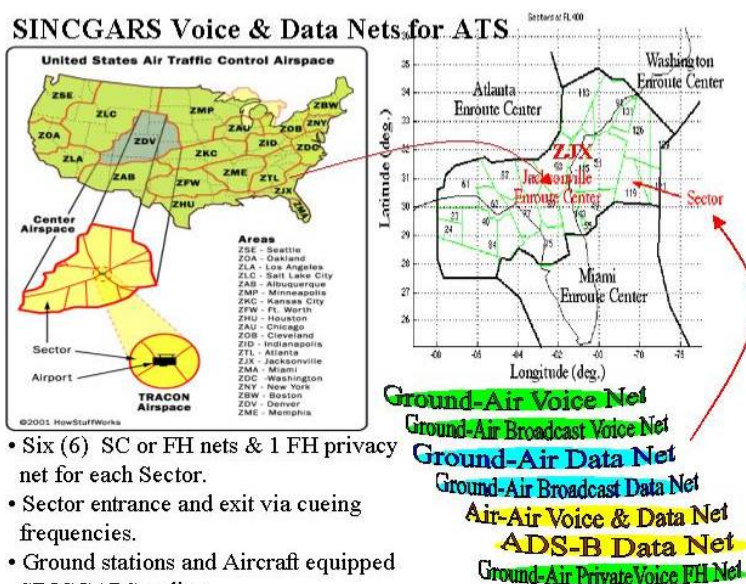


Figure 3.8-2: SINGARS Frequency, Time and Functions Diversity

3.8.3.1.3 SINGARS Air Interface Description: PHY, MAC, and Network

The characteristics of the SINGARS Air Interface are provided in table 3.8-3 below.

Table 3.8-3: SINGARS Air Interface Description

Duplexing scheme	SINGARS is a simplex system
Multiple-Access scheme	SINGARS is a listen PTT and Carrier Sense Multiple Access (CSMA) system
Modulation Types	AM and FM (FSK Voice and BFSK data)
Vehicle Speed Supported	500 knots, SINGARS is installed on a wide variety of military fixed wing and rotary wing aircraft (e.g., F-16, C-130, OA-10, UH-60,...) and ground vehicles.
Maximum Range Supported	40 Km, dependent on specific radio and amplifier
Signal Bandwidth	98% within +/-12.5 KHz on each frequency
Proposed Frequency Band	Current ATC band, 118 to 137 MHz

3.8.3.2 Link 16

Link 16 is a message standard and waveform(s). Link 16 terminals, integrated into host systems, generate overhead messages required for Link 16 network operation, and position reports. Host mission computers (application layer) generate Link 16 messages. The Link 16 waveform (Physical, Link, and Network layers) is transmitted by Joint Tactical Information Distribution System (JTIDS) and Multifunctional Information Distribution System (MIDS) terminals. The current production terminals are:

- MIDS LVT-1: The standard fully-capable MIDS terminal including voice and TACAN integration.
- MIDS LVT-2: Customized MIDS for Army/Ground Environment use. It features no voice or TACAN, a single blower and power supply, and spare slots for growth.

- MIDS LVT-3 [Also known as Fighter Data Link (FDL)]: Reduced capability MIDS terminal specially customized for the F-15.
- MIDS LVT-MOS (MIDS On Ship): MIDS LVT-1 terminal customized for Navy ship and ground platforms and features a 1 kW High Power Amplifier.

In addition, host systems and JTIDS/MIDS terminals can be interfaced with IP networks land-lines and satellite links for forwarding of messages per MIL-STD-3011 Joint Range Extension Application Protocols (JREAP).

Link 16 uses a combination of Frequency Division Multiple Access (FDMA), Code Division Multiple Access (CDMA), Time Division Multiple Access (TDMA) and Network Participation Groups (NPGs) to construct Link 16 Networks. Link 16 “nets” are the pseudo random frequency hopping patterns of Link 16’s 51 frequencies. The use of different frequency hopping patterns (FDMA) and pseudorandom coding (CDMA) on individual user transmissions, provides the capacity for the system to operate simultaneously on up to 127 nets in a single Network. Approximately 20 nets can operate in a geographic area without significant mutual interference. Link 16 participation the beyond frequency hopping function is via time slots (TDMA), where participants are assigned time slots for transmission of their messages and receive information in those time slots not assigned to them. The fixed Time Slot duration is 7.8125 ms and the basic Link 16 time frame is 12 seconds containing 1536 time slots. Link 16 terminals can operate in any “net” in any time slot as determined by time slot assignments. However, terminals can not operate (send or receive) on two different “nets” at the same time. NPG defines a set of information exchange that supports a specific function, for example Surveillance. Time slots are allocated to each Link 16 terminal/platform to support their participation in those NPGs applicable to their mission. The same set of time slots may be used for more than one “net” simply by assigning a different frequency-hopping pattern to each. There are 31 standard internationally agreed to NPGs, among which the following are specifically applicable to ATS:

- Initial Entry
- Network Management
- Precise Participant Location and Identification (PPLI) and Status
- Surveillance
- Air Control
- Voice A and Voice B (2 concurrent channels)

A Link 16 Network comprises all the NPGs, all the “nets” and the participant time slots assignments. Successful operation of a Link 16 network is based on a detailed and accurate Network design. The terminals of all participating units must be provided with parameters generated by a network design facility to ensure a common definition of network characteristics and coordination of time-slot usage. Network design is a critical process when operating Link 16 because though it is possible to switch from one design to another, it is not possible to change them on-line, so contingencies and scenarios must have been previously foreseen. Link 16 Messages are defined in MIL-STD-6016C. The messages applicable to ATS are addressed in paragraph 3.8.4.2.1 below, and these messages could easily be adapted for civil use. They are generated by military host computer systems, with the exception of Precise Participant Location and Identification (PPLI) messages, which are generated by JTIDS or MIDS terminals based on platform/site navigation system inputs and relative navigation among terminals. Addressed messages often require action by the recipient and many of the messages include provisions for operator acknowledgements; for example WILCO (“will comply”), CANTCO (“can’t comply”) or HAVCO (“have complied”).

3.8.3.2.1 Link 16 Services Provided and Key Features

Link 16 transmissions are pseudo-randomly hopped among 51 frequencies spaced at 3 MHz intervals in the 969 to 1206 MHz band. Frequencies within 20 MHz of the two Identification Friend or Foe (IFF)

frequencies at 1030 \pm 20 MHz and 1090 MHz are not used. Link 16 can operate in three different communication modes:

- encryption and frequency hopping.
- encryption and a single frequency (969 MHz).
- no encryption, single frequency (969 MHz).

As indicated above, before commencing operations, each Link 16 terminal is provided the Net(s) hopping information and Time Slot Assignments (mission data load) for each assigned NPG. Time slot assignments include the below listed Access Methods for each slot.

- Dedicated Access consists of granting network access to each participating unit according to a reporting rate.
- Contention (Random) Access allows a number of transmitters to share use of Time Slots in a pool on a probabilistic basis. If two or more users transmit in the same time slot, any given receiver receives the nearest transmission and rejects the others.
- Time Slot Reallocation (TSR) is an access method in which terminals share access to a common pool of time slots based on their expected demand. For access management, each user calculates its present time slot needs during an access period of 6 to 48 seconds and transmits a reservation announcement message during each access period. The terminal receives the reservation announcements from other users, automatically calculates the user needs and reserves a unique set of time slots for that user for the next access period.
- Demand Access is used to support push-to-talk voice functions and transmission of non-periodic data such as requested image files. In demand access mode other users monitor demand-access time-slot blocks for use. There is no “step-on” protection, so if two users demand a block at the same time, contention results (see above).

Link 16 terminals can select from a number of different message formats within a timeslot depending upon the type of message being supported, the throughput demand, and the required anti-jam performance. These timeslot formats differ in the number of data pulses, the amount of error detection and correction and the amount of data redundancy. Link 16 uses a word size of 70 bits, which is the number of data bits available to the Link 16 user applications on each Link 16 word. Four different data packing structures may be used:

- Standard Double Pulse (STDP): Transmits 3 words, with each symbol transmitted on two consecutive pulses in the slot. Affords the lowest throughput but the highest level of jam resistance.
- Packed-2 Double Pulse (P2DP): Transmits 6 words with each symbol transmitted on two consecutive pulses in the slot by using more message time and less guard time in the timeslot.
- Packed-2 Single Pulse (P2SP): Allows the transmission of 6 words by putting different data in each of two adjacent pulses, at the cost of less jam and multi-path resistance.
- Packed-4 Single Pulse (P4SP): Allows the transmission of 12 words, by putting different data in each of two adjacent pulses and by using more message time and less guard time in the timeslot. This provides the highest throughput at the cost of no redundancy and lower jam resistance.

3.8.3.2.2 Link 16 Functional Architecture

The Link 16 functional architecture is illustrated in figure 3.8-3 below. This illustration shows its relationship with joint air sea and land military operations and connectivity to SINCGARS via Tactical Operations Centers (TOCs), Air Operations Centers (AOCs) and ABCCCs. In the illustration, there is a network supporting Naval operations. F-14Ds and an E-2C are providing the outer air defense for a Navy Task Force. This Air Defense Network is connected to a Tactical Operations Network consisting of ABCCC, AWACS and F/A-18s operating off the Navy Task Force CV (aircraft carrier). These networks

are connected via Joint Range Extension (JRE) Application Protocol (JREAP) SATCOM connections at the CV and the AOC, which are LOS connected to the Air Defense and Tactical Operations networks respectively.

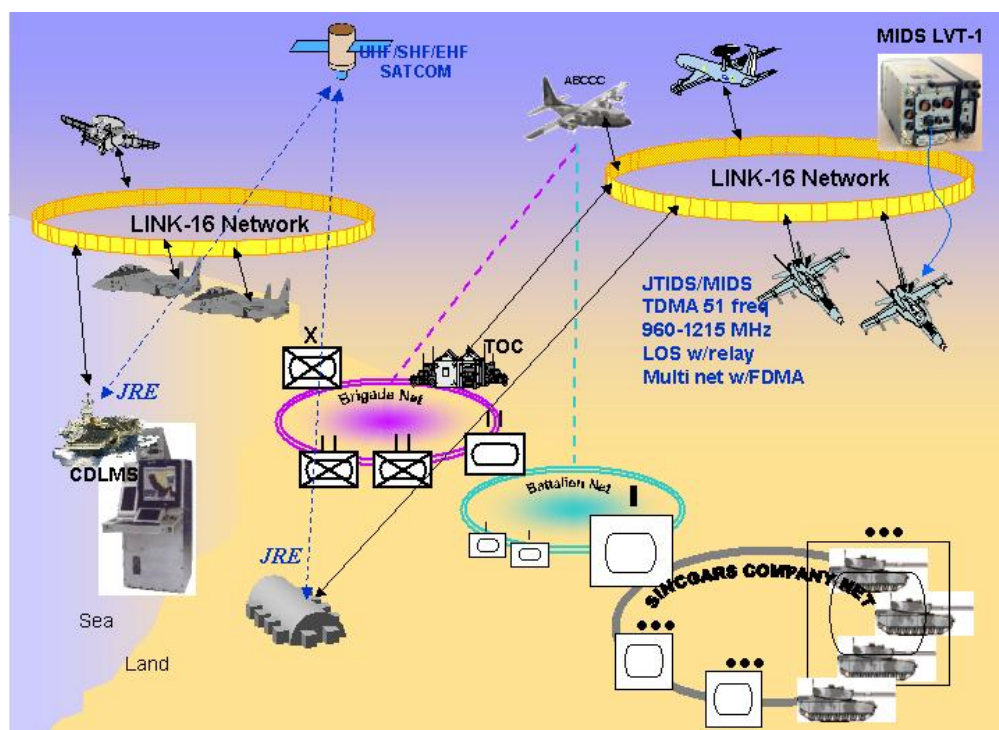


Figure 3.8-3: Link 16 Architecture

Link 16 Networks are frequency, time and functionally diverse. Frequency diversity (FDMA) is provided via pseudo random FH that supports multiple nets to operate in parallel without interference. Time diversity (TDMA) is provided by the establishment of a fixed time frame with a fixed number of time slots that are allocated to each of the participants based on their respective missions. Functional diversity is provided via the allocation of the Link 16 messages by type to Network Participation Groups (NPGs). In figure 3.8-4 below, the frequency, time and functions diversity of Link 16 are illustrated in the context of Link 16 Network formulation.

Network development is mission oriented with each participant being allocated sufficient time slots to accomplish his/her mission. The network development process is complicated by the mission processing performance characteristics of the participants. Prior to each mission the platforms (AWACS, F/A-18, TOC, Carrier,...) receives or updates the appropriate mission network. That is the network(s) are loaded into the Link 16 terminals (radios) and host platforms via a variety of fill devices.

The Initial Entry and Round Trip Timing and Net Management NPGs support Link 16 the self-forming and self-healing attributes of the Link 16 Networks. In addition, Net Management NPG supports the relay of messages beyond LOS (BLOS) by air C2 platforms (e.g., AWACS and E-2C Hawkeye). The voice capability of each net is two channels (NPGs Voice A and Voice B) with voice access via listen before push-to-talk (PTT). Notice, voice is relayed within the Network but not via JRE to other networks.

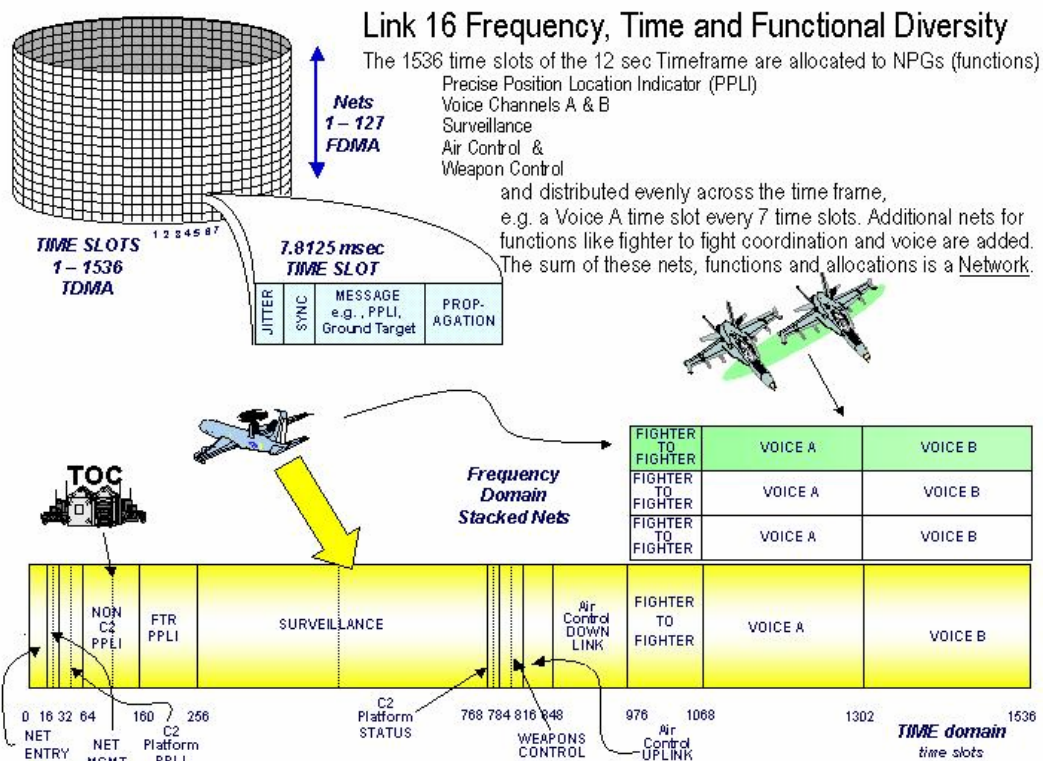


Figure 3.8-4: Link 16 Frequency, Time and Functions Diversity

In the following figure 3.8-5, a notional functional architecture of Link 16 supporting ATS is depicted. In this architecture, Link 16 Networks are assigned to Sectors to support the ATS voice and data communications needs to be discussed in subsequent paragraphs. In particular, the graphic indicates the assignment of 5 each stacked nets for voice and data communications between the ground and in-sector 119 aircraft, as well as between in sector aircraft. Access to these networks is to be via frequency hopping nets specific to the Sector. Notice, this architecture is consistent with how Link 16 operates and in bordering sectors different frequency hopping patterns would be used. However, Link 16 capabilities to support ATS based on specific needs are addressed in subsequent sections.

Link 16 Networks for ATS

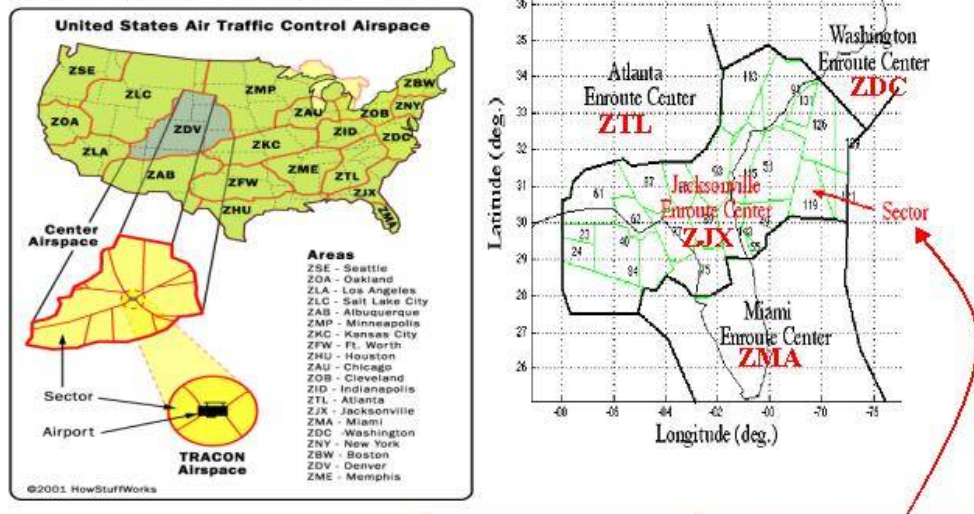


Figure 3.8-5: Notional Functional Architecture of Link 16 supporting ATS

3.8.3.2.3 Link 16 Air Interface Description: PHY, MAC, and Network

The characteristics of the Link 16 Air Interface are provided in table 3.8-4 below.

Table 3.8-4: Link 16 Air Interface Description

Duplexing scheme	Basically, Link 16 is a simplex system. However, the TDMA and FDMA characteristics of the system coupled with a multiple R/T channel terminal provide a half-duplex like capability.
Multiple-Access scheme	TDMA (assigned time slots) per FDMA (prescribed frequency hopping)
Modulation Types	MSK 32 bit Pseudorandom Sequence
Vehicle Speed Supported	Mach 1 plus, terminals are installed in F-14D and F/A-18C aircraft
Maximum Range Supported	Dependent on amplifier. 100 to 300 miles
Signal Bandwidth	3.75 MHz at 3 db points on each hopped frequency
Proposed Frequency Band	DME Band 960 to 1024 MHz

3.8.4 Concept of Use: Application to Aeronautical A/G Communications

3.8.4.1 SINCGARS

Below, the system's capabilities to support ATS communications needs and the potential impacts of the system to aircraft and ATS ground facilities are discussed.

3.8.4.1.1 ATS Communications Needs

Voice Need 1. Pilot-Controller Talk Group: this is essentially the setup and maintenance of a group conference call between a Controller and all of the Pilots in the domain of that Controller.

SINGARS Capability. SINGARS is a network system. The controller and the pilots/aircraft being controlled would form a SINGARS network. SINGARS voice communications is PTT and CSMA. The controller would be the Master node for the network. The network would cover the controller's geographic area of responsibility. The network could be frequency hop (FH) or single channel (SC) (single frequency). Pilots/Aircraft entering the area would tune to the area (sector) designated SC, or use the area (sector) designated cueing frequency to obtain the FH via ERF from the controller to enter the network.

Voice Need 2. Pilot-Controller Selective Addressing: supports a call and dialog between a Controller and a selected Pilot that is not overheard by other Pilots

SINGARS Capability. Providing the pilot/aircraft and the controller with a private line can be accomplished via the establishment of an additional SINGARS network for each line needed. (It is expected that only one network would be needed as private lines would only be needed on at a time.) The establishment of these network(s) could be accomplished via another specifically designated cueing frequency, where the pilot/aircraft requested the private connection. If the controller determines a need for the private line, a simple voice command from the controller to the pilot would suffice for the pilot to send the designated cueing frequency for a private line. The private line could be either SC or FH.

In terms of the radio equipment, the controller would need to maintain the party line with pilots/aircraft in the designated area of control while having private lines to specific pilots/aircraft. This means that the controller's SINGARS capability would have to be several RTs

Voice Need 3. Direct Pilot-Pilot: the candidate allows Pilots to talk directly with each other without requiring other facilities as an intermediary.

SINGARS Capability. All the pilots in a geographic zone/sector area are connected in the SINGARS network and pilots via "call signs" can communicate. However, the network is a party line with priority for the controller to manage the air space.

Where the aircraft are relatively close together, pilot-pilot communications can be conducted on a non-interference basis via reducing transmission power. If aircraft have multiple RT capabilities, pilot-pilot communications can be established via a prior coordination on the party line. The process would be to establish a new SINGARS network via a cueing channel with the Network Controller providing the SC or FH via ERF. This network could also support data communications between pilots/aircraft.

Voice Need 4. Broadcast: The technology provides a voice broadcast capability.

SINGARS Capability. The system has no capability to provide this service without interfering with voice other services. Basically, the airplanes and the ground stations need an additional dedicated receiver channel, e.g., a "Guard" like channel. There are adequate channels in the 30 to 88 MHz band to dedicate guard (Broadcast) channels for each air control sector. In the ATC band (118 to 138 MHz) a frequency could be made available. Either of these frequencies could support both voice and data. Airborne radios would need another receiver to support this service.

Basic Data Need 1. Air-to-Ground and Ground-to-Air Addressed Data Transport

SINGARS Capability. The SINGARS network supports both voice and data. Communications can be accomplished via SC or FH. For data communications from a mobile user (aircraft) to the ground, communications would be via addressed packets [Mobile (wireless) IP (v4 or v6)]. For data communications from the ground to a specific aircraft, communications would be via addressed packets [Mobile (wireless) IP (v4 or v6)]. For data communications from the ground to a Data Group (group of aircraft), it is envisioned that the communications would be via broadcast packets [Mobile (wireless) IP (v4 or v6)], all aircraft in the group would have a common address for these communications.

Basic Data Need 2. Ground-to-Air Broadcast Data Transport

SINGARS Capability. The system has no capability to provide this service without interfering with other services. Basically, the airplanes and the ground stations need an additional dedicated receiver

channel, e.g., a “Guard” like channel or another 30 to 88 receiver that is set up with a different FH for this service. There are adequate channels in the 30 to 88 MHz band to dedicate guard (Broadcast) channels for each air control sector. In the ATC band (118 to 138 MHz) a frequency could be made available. Either of these frequencies could support both voice and data. Airborne radios would need another receiver to support this service.

Expanded Data Need 1. ADS-B (Automatic Dependent Surveillance-Broadcast) Broadcast of each aircraft’s position on a regular basis to ground stations without interfering with other ATM functions

SINGARS Capability. SIN(single)CGARS has the capability to report its location (position) at each voice transmission (PTT trigger) via the radio’s connection to a GPS receiver. It would be possible, to modify the radio to do this on regular basis in lieu of the PTT trigger or in addition to the PTT trigger. In addition, a separate frequency (channel) could be set up for this function, like a “GUARD” channel, and the transmitter would transmit its position every second or ten seconds. Or an additional RT Channel would be needed to support this function. Notice, that an extra RT channel [now a dual channel Ground and Airborne Radio System (DULGARS)] would also support in parallel the Voice and Data Broadcast needs.

Expanded Data Need 2. Pilot-Pilot Data Transport:

SINGARS Capability. For data communications between mobile users (aircraft) in a Data Group: communications would be via addressed packets [Mobile (wireless) IP (v4 or v6)] for specific aircraft to aircraft communications and via broadcast packets [Mobile (wireless) IP (v4 or v6)] from one aircraft to all the aircraft in the Data Group. Notice, IP networks require a continuous registration process that would support everyone in the group knowing each others address. These communications could be accomplished via SC or FH.

3.8.4.1.2 *SINGARS Aircraft Impacts*

Table 3.8-5 below summarizes the potential impacts of using SINGARS for ATS to aircraft operating in the controlled airspace.

Table 3.8-5: SINGARS Aircraft Impacts

Impact Item	Impact Description
New Radio	Yes, the Radio will require Data Interface, GPS Interface, Wireless IP interface, and least dual RT capability
New Antenna	Yes, Assuming that the RTs are specified to work with the existing antennas. However, if new antennas were developed, provided additional performance and were form and fit replacements of existing antennas, then new antennas would be applicable. Omni antenna coverage required for Air-to-Air communications.
Antenna Diplexer	Yes
Timing Source	Yes (GPS will support this need)
Additional Equipment	Yes, GPS, CDU and Data Communications Processor
Assumptions	<p>1) The ATM architecture in 2015 is similar to the current architecture in terms of numbers, locations and functions of the ground stations.</p> <p>2) The use of SINGARS technology to support the 8 ATM services indicated above will require updated RTs to transition SINGARS to the 118 to 138 MHz band.</p> <p>3) Given the 2015 schedule, this upgrade will employ JTRS or/similar waveform programmable R/T technologies.</p> <p>4) The current ATC Voice allocation is 118 to 122, 124 to 129 and 132 to 137 MHz . At a 25 kHz channel width there are 560 channels. Given current technology (AN/ARC-210, AN/PRC-117 and AN/PSC-5), channel widths/spacing of 5, 6.25 and 8.33 kHz appear to be quite reasonable. In this context, a minimum of 1680 frequency channels and potentially a maximum of 2800 channels would be available. Based on the 1200 channels needed for the FH to support a USA heavy division, at a minimum the 8.33 kHz channel spacing will be required.</p> <p>5) To support data communications, Wireless IPv6 (address space) will have to be employed.</p>

3.8.4.1.3 *SINGARS Ground Impacts*

Table 3.8-6 below summarizes the potential impacts of using SINGARS for ATS to the ground infrastructure.

Table 3.8-6: SINCGARS Ground Impacts

Impact Item	Impact Description
New Radio	Yes, Each controller (sector) will need several SINCGARS RTs to support private channels, Broadcast and ADS-P.
New Antenna	Yes, Assume that new radios will be specified to be compatible with existing antennas. However, expect that new technology will improve antenna performance (gain and pointing accuracy) to the extent that new antennas will be a high priority.
Antenna Diplexer	Yes
Timing Source	Yes, New timing source should be a timing ensemble [GPS time receiver with cross latched rubidium frequency standards integrated with a time code generator]
Additional Equipment	Yes, It is expected that the new channel spacing and the addition of data communications will necessitate new CDU capabilities, as well as on-line data archives.
Assumptions	<p>1) The ATM architecture in 2015 is similar to the current architecture in terms of numbers, locations and functions of the ground stations.</p> <p>2) Given the 2015 schedule, the radio upgrade will employ JTRS or/similar waveform programmable Radio (R/T) technologies, that are compatible with the 118 to 138 MHz legacy waveforms.</p> <p>3) If a SATCOM capability is envisioned, then new dedicated antennas to geo-stationary orbit communication satellites will be required. Further, for polar coverage, additional ground stations would be needed with SATCOM and fiber connectivity.</p>

3.8.4.2 Link 16.

Below, the system's capabilities to support ATS communications needs, and the potential impacts of the system to aircraft and ATS ground facilities are discussed.

3.8.4.2.1 ATS Communications Needs

Voice Need 1. Pilot-Controller Talk Group: this is essentially the setup and maintenance of a group conference call between a Controller and all of the Pilots in the domain of that Controller.

Link 16 Capability. Link 16 is a network system that supports 2 concurrent digitized voice nets on a subset of a single frequency-hopped Link 16 channel through a single radio. Pilots and controllers can select from one of 127 selectable channels on each of the voice nets. The controller and the pilots/aircraft being controlled would form a voice network. Link 16 voice communications is PTT. The voice net covers the controller's geographic area of responsibility. Each controller/controlled aircraft group has its own frequency-hopped channel, and up to four channels are allowed in a geographic radius of 200 miles during routine CONUS operations. All pilots can hear controller and other aircraft voice conversations. End-to-end latencies are under 0.2 seconds. Air control in Link 16 is primarily by data link, and therefore voice is only used to supplement data link communications.

Voice Need 2. Pilot-Controller Selective Addressing: supports a call and dialog between a Controller and a selected Pilot that is not overheard by other Pilots

Link 16 Capability. Currently, this service is not supported. However, the Link 16 system architecture can support this service.

Voice Need 3. Direct Pilot-Pilot: the candidate allows Pilots to talk directly with each other without requiring other facilities as an intermediary.

Link 16 Capability. Link 16 is a network system that supports 2 concurrent digitized voice nets on a subset of a single frequency-hopped Link 16 channel through a single radio. Link 16 voice communications is PTT. This service can be provided on the same voice net as the Pilot-controller Talk Group or on the second selectable voice channel concurrent with the Pilot-Controller Talk Group. Air-to-air communications in Link 16 is primarily by data link, and therefore voice is only used to supplement data link communications.

Voice Need 4. Broadcast: The technology provides a voice broadcast capability.

Link 16 Capability. Broadcast voice can occupy one of the 2 concurrent voice nets in Link 16 and would be on a different selectable channel from direct Pilot-Pilot voice. This channel is typically used to support controller-controller communications (e.g. hand over of aircraft from one controller to another) as a supplement to data link communications supporting the same function.

Basic Data Need 1. Air-to-Ground and Ground-to-Air Addressed Data Transport

Link 16 Capability. Air Control is an addressed/ acknowledged multi-channel 2-way service between controllers and the aircraft under their control on a subset of a common frequency-hopped channel. Each controller/controlled aircraft group has its own frequency-hopped channel, and up to four channels are allowed in a geographic radius of 200 miles during routine CONUS operations. The following Link 16 data link messages currently support this service:

- J12.1 Vector—Used by controllers to send vector information (course and speed) to aircraft. Vectors are given for navigation, and air traffic control.
- J12.3 Flight Path—Used by controllers to provide aircraft with multiple-leg flight path information (up to 15 waypoints).
- J12.4 Controlling Unit Change Message—Used to provide new controller information (including radio channel) to an aircraft prior to handoff to the new controller. Also used by aircraft to initiate control procedures with a new controller or to effect a change of controller.

Basic Data Need 2. Ground-to-Air Broadcast Data Transport

Link 16 Capability. Surveillance and Airfield Status are broadcast services to all aircraft in a geographic area on a subset of a common frequency-hopped channel. The following Link 16 messages support this service:

- J3.0 Reference Point—Provides information about geographic references, such as hazardous or restricted areas.
- J3.1 Emergency Point—Provides the location and type of an emergency that requires search and rescue; for example, a downed aircraft or disabled vessel.
- J3.2 Air Track—Provides identity, position, course, and speed of air tracks detected by surveillance systems such as primary radars and radar beacon systems.
- J3.5 Land Point/Track—Provides identity, position, course, and speed of land vehicles detected by surveillance systems such as radars. Could be used to prevent runway incursions at airports.
- J13.0 Airfield Status—Used to report operational status of airfields, runways and airfield facilities, including local weather conditions, snow and ice, etc.
- Other messages could be developed to support additional services.

Expanded Data Need 1. ADS-B (Automatic Dependent Surveillance-Broadcast)

Broadcast of each aircraft's position on a regular basis to ground stations without interfering with other ATM functions

Link 16 Capability. PPLI and Status is a broadcast service available to all aircraft and controllers in a geographic area on a subset of a common frequency-hopping channel, and is similar to ADS-B. The following Link 16 messages support this service:

- J2.2 Air PPLI—Provides all participating units information about other airborne units on the Link 16 network. Used by aircraft to provide network participation status, identity, position, course, speed and relative navigation data.
- J13.0 Airfield Status—Used to report operational status of airfields, runways and airfield facilities, including local weather conditions, snow and ice, etc.
- J13.2 Air Platform and System Status—Provides the current status of an aircraft to include fuel, operational status, and on board systems' status.

Expanded Data Need 2. Pilot-Pilot Data Transport:

Link 16 Capability. Fighter-Fighter is multi-channel 2-way service among aircraft on a subset of a common frequency-hopped channel. This channel uses a combination of addressed and broadcast messages. Each aircraft group has its own frequency-hopped channel, and up to four channels are allowed in a geographic radius of 200 miles during routine CONUS operations. The Link 16 data link messages used on fighter-fighter channels are designed for uniquely military operations; however other messages could be developed to support ATM services.

3.8.4.2.2 *Link 16 Aircraft Impacts*

Table 3.8-7 below summarizes the potential impacts of using Link 16 for ATS to aircraft operating in the controlled airspace.

Table 3.8-7: Link 16 Aircraft Impacts

Impact Item	Impact Description
New Radio	Yes, Radio will require modification of data interface from MIL-STD-1553 or Ethernet to standard aircraft interface, such as ARINC 429. Two 16 KBPS vocoders are built into equipment, and use standard aircraft ICS interfaces. Alternatively, equipment could be modified to use the VDL 3 vocoder algorithm at 4800 BPS.
New Antenna	No, Can use current aircraft DME antennas with Antenna Duplexer
Antenna Diplexer	Yes
Timing Source	No, aircraft synchronization to ground sites
Additional Equipment	Yes, Data Communications Processor
Assumptions	<p>1) The ATM architecture in 2015 is similar to the current architecture in terms of numbers, locations and functions of the ground stations.</p> <p>2) The use of Link 16 technology to support the ATM voice and data services indicated above will require FAA and DoD to agree to share the current Link 16 (JTIDS/MIDS) spectrum, which allocates the system to aeronautical mobile/fixed and ground mobile services on a not-to-interfere basis with current and future ARNS systems in the 960 to 1215 MHz frequency band.</p> <p>3) Given the 2015 schedule, this upgrade will employ JTRS or/similar waveform programmable R/T technologies compatible with the 960 to 1215 MHz Link 16 waveform.</p> <p>4) To support data communications, aircraft manufacturers would have to implement a Link 16 message processor capability. Several vendors can provide software to implement these messages. Alternatively, the Link 16 system can be used as a carrier for FAA-developed data link messages providing similar services.</p>

3.8.4.2.3 *Link 16 Ground Impacts*

Table 3.7 below summarizes the potential impacts of using Link 16 for ATS to the ground infrastructure.

Table 3.7: Link 16 Ground Impacts

Impact Item	Impact Description
New Radio	Yes, Radio will require modification of data interface from MIL-STD-1553, X.25, or Ethernet to FAA standard interface. Will also require processors at ATC center sites and remote radio sites to provide remoting of the radios. Two 16 KBPS vocoders are built into equipment, and use standard ICS interfaces. Alternatively, equipment could be modified to interface with the VDL 3 vocoders at 4800 BPS.
New Antenna	Yes, Requires mast-mounted, omni-directional antenna suitable for operation over 960 to 1215 MHz. For radios used at sites that also have DME or ATCRBS beacons, special EMI suppression/mitigation techniques may be required, depending on antenna separation.
Antenna Diplexer	
Timing Source	Yes, New timing source should be a timing ensemble [GPS time receiver with cross latched rubidium frequency standards integrated with a time code generator]
Additional Equipment	Yes, Data Communications Processor
Assumptions	<p>1) The ATM architecture in 2015 is similar to the current architecture in terms of numbers, locations and functions of the ground stations.</p> <p>2) Given the 2015 schedule, the radio upgrade will employ JTRS or/similar waveform programmable Radio (R/T) technology, compatible with the 960 to 1215 MHz Link 16 waveform.</p> <p>3) Assume that new radios will be specified to be compatible with currently available antennas. However, expect that new technology will improve antenna performance (gain and pointing accuracy) to the extent that new antennas will be a high priority.</p> <p>4) If JREAP is also used to interconnect ground facilities via SATCOM (vice fiber) envisioned, then new dedicated antennas to the communication satellites will be required.</p> <p>5) To support data communications, aircraft manufacturers would have to implement a Link 16 message processor capability. These capabilities with minor updates would support ground message processing. Several vendors can provide software to implement these messages. Alternatively, the Link 16 system can be used as a carrier for FAA-developed data link messages providing similar services.</p>

3.8.5 *Evaluation Summary and Scores*

The SINCGARS and Link 16 technologies have been evaluated per the criteria established for each of the ATS communication needs.

Table 3.8-9 provides a scoring summary for SINCGARS. The rationale for assigned scores is in table 3.8-10.

Table 3.8-9: SINCGARS Evaluation Sheet

	Criteria	Surface	Terminal	En Route	Oceanic	Polar
Voice Needs	1					
Pilot-Controller Talk Group	1A1					
Pilot-Controller Selective Addressing	1A2					
Direct Pilot-Pilot	1A3					
Broadcast capability	1A4					
Capacity provided	1B1					
Address space	1B3					
Aircraft mobility management	1C1					
Latency	1C2					
Basic Data Needs	2					
A/G and G/A Addressed Data Transport	2A1					
Ground-to-Air Broadcast Data Transport	2A2					
Aggregate Data Rate	2B1					
Number of Users	2B2					
Uplink and Downlink Priority Levels / QoS	2C1					
Latency	2C2					
Enhanced Data	3					
ADS-B	3A1					
Pilot-Pilot Data Transport	3A2					
Aggregate Data Rate	3B1					
Technology Readiness Level	4					
Standardization Status	5					
Certifiability	6					
Ground Infrastructure Cost	7					
Cost to Aircraft	8					
Spectrum Protection	10					
Security	11					
Transition	12					

Table 3.8-10: SINCGARS Evaluation Score Rationale

SINCGARS Evaluation	Score	Rational
Pilot-Controller Talk Group	Green (S, T and E) Red (O and P)	LoS system; LBPPT is the native protocol
Pilot-Controller Selective Addressing	Green (S, T and E) Red (O and P)	LoS system; private line is done by setting up a net between controller selected pilot on the fly; net defined by a dedicated channel (i.e., hopset).
Direct Pilot-Pilot	Green (all domains)	Native capability; half duplex—everyone in the net hears
Broadcast capability	Green (S, T and E) Red (O and P)	LoS system; net is formed for the broadcast
Capacity provided	Red (all domains)	System uses 25 kHz channels so that if placed in aero VHF band, capacity is not increased if only orthogonal hopsets are used; if non-orthogonal hopsets are allowed, then a modest amount of capacity increase may be supported.
Address space	Yellow (all domains)	Addressing requires a dedicated net (hopset) so that the use of addressing uses channels inefficiently
Aircraft mobility management	Yellow (S, T and E) Red (O and P)	Mobility management is handled via procedures
Latency	Green (all domains)	DoD criterion for 16 kbps voice is 200 ms
A/G and G/A Addressed Data Transport	Green (S, T and E) Red (O and P)	Net has a variable message format (VMF) header that includes an address
Ground-to-Air Broadcast Data Transport	Green (S, T and E) Red (O and P)	Broadcast message is native in VMF header
Aggregate Data Rate	Yellow (all domains)	A 16 kbps data rate is supported in each channel
Number of Users	Green (all domains)	VMF address space is > 200
Uplink and Downlink Priority Levels/QoS	Red (all domains)	MAC is CSMA so that QoS is not provided over the air interface; could allocate a channel for each priority level, but this is not efficient use of spectrum.
Latency	Green (all domains)	Latency should be < 200 ms for data.
ADS-B	Green (all domains)	Air-air broadcast within a net is supported
Pilot-Pilot Data Transport	Green (all domains)	Air-air broadcast within a net is supported
Aggregate Data Rate	Red (all domains)	16 kbps is << 280 kbps so that this is Red
Technology Readiness Level	Green	SINCGARS is deployed—only requires development for VHF spectrum
Standardization Status	Red	There are no publicly available standards
Certifiability	Yellow	There is a high assurance level in the hardware and software
Ground Infrastructure Cost	Yellow	The FH radio is relatively high cost; also, more than one radio is required to do selective addressing.
Cost to Aircraft	Yellow	Combination of FH and multiple radio installations (to support talk group and selective addressing) makes this relatively expensive
Spectrum Protection	Green	The VHF band is protected spectrum
Security	Green	Provides support for A and I
Transition	Yellow	Potential interference to fixed frequency

Table 3.8-11 provides a scoring summary for Link 16. The rationale for assigned scores is in table 3.8-12.

Table 3.8-11: Link 16 Evaluation Sheet

	Criteria	Surface	Terminal	En Route	Oceanic	Polar
Voice Needs	1					
Pilot-Controller Talk Group	1A1					
Pilot-Controller Selective Addressing	1A2					
Direct Pilot-Pilot	1A3					
Broadcast capability	1A4					
Capacity provided	1B1					
Address space	1B3					
Aircraft mobility management	1C1					
Latency	1C2					
Basic Data Needs	2					
A/G and G/A Addressed Data Transport	2A1					
Ground-to-Air Broadcast Data Transport	2A2					
Aggregate Data Rate	2B1					
Number of Users	2B2					
Uplink and Downlink Priority Levels / QoS	2C1					
Latency	2C2					
Enhanced Data	3					
ADS-B	3A1					
Pilot-Pilot Data Transport	3A2					
Aggregate Data Rate	3B1					
Technology Readiness Level	4					
Standardization Status	5					
Certiability	6					
Ground Infrastructure Cost	7					
Cost to Aircraft	8					
Spectrum Protection	10					
Security	11					
Transition	12					

Table 3.8-12: Link 16 Evaluation Score Rationale

Link 16 Evaluation	Score	Rational
Pilot-Controller Talk Group	Green (S, T and E) Red (O and P)	Voice is a native capability. Technology requires ground infrastructure.
Pilot-Controller Selective Addressing	Yellow (S, T and E) Red (O and P)	Some modification would be required to provide selective addressing function. Technology requires ground infrastructure.
Direct Pilot-Pilot	Green (all domains)	Voice is a native capability. No ground infrastructure is required to provide mobile to mobile communications.
Broadcast capability	Green (S, T and E) Red (O and P)	Voice is a native capability. Technology requires ground infrastructure.
Capacity provided	Yellow (all domains)	Should provide 240 (8 channels/net x 30 nets) additional assignable voice channels via a combination of TDMA and FDMA ¹⁰³
Address space	Yellow (all domains)	15 bit address space is provided. Since no A/G communications capability exists to remote regions (O and P) these were marked red.
Aircraft mobility management	Green (S, T and E) Red (O and P)	Orderwire would be used to uplink next net information.
Latency	Green (all domains)	Latency should be less that 200 ms. This assumes a CVSD vocoder implementation (16 kbps).
A/G and G/A Addressed Data Transport	Green (S, T and E) Red (O and P)	Link 16 data messages provide an address field. Reliable delivery is ensured due to defined ack. protocols.
Ground-to-Air Broadcast Data Transport	Green (S, T and E) Red (O and P)	This is a native capability of the technology.
Aggregate Data Rate	Green (all domains)	System will provide 115 kbps per net.
Number of Users	Green (all domains)	15 bit address space allows ~ 30000 addresses
Uplink and Downlink Priority Levels/QoS	Green (all domains)	Orderwire reservation request allows priority assignment to the most urgent data.
Latency	Yellow (all domains)	6 second look-ahead reservation means that Class B data cannot be routinely met
ADS-B	Green (all domains)	EUROCAE study concluded it could meet ADS-B requirements
Pilot-Pilot Data Transport	Green (all domains)	Native capability
Aggregate Data Rate	Yellow (all domains)	Enhanced throughput mode will provide up to ~1 Mbps at close range
Technology Readiness Level	Yellow	Modifications noted above require some development
Standardization Status	Red	Standards are not publicly available
Certifiability	Yellow	There is a high assurance level in the hardware and software
Ground Infrastructure Cost	Red	Estimated cost of terminals ~ \$50K; check EUROCAE reports
Cost to Aircraft	Yellow	Estimated cost is equal to 4.7 x ARINC 716 8.33/25 kHz DSB-AM analog receiver
Spectrum Protection	Yellow	Target band is the DME band
Security	Green	Link 16 provides authentication and integrity.
Transition	Yellow	Will require clearing the band of the DME

3.9 APC Telephony

3.9.1 Overview of the Family

Airline Personal Communications (APC) telephony is allocated a pair of 2 MHz bands and currently supports an FDD circuit service. The major parameters of the system are as follows:

- Allocated Spectrum
 - 849 to 851 MHz ground to air
 - 894 to 896 MHz air to ground
- Channelization: spectrum Divided into ten (10) channel blocks; each block is subdivided into multiple 6 kHz channels:
 - 6 control channels
 - 29 communications channels
- Circuit voice or circuit data provided on each communications channel
- Ground Stations:
 - Regular lattice of ground cell sites located within 1.6 kilometers of the 97 site locations identified by coordinates in section 22.859 of FCC rules

- An entire channel block is assigned to a cell site

An FCC NOTICE OF PROPOSED RULE MAKING, April 17, 2003, Released: April 28, 2003, Docket No. 03-103, will revise spectrum sharing rules that will determine future use and technology in this band. There are a number of service providers vying to utilize this spectrum more efficiently pending FCC rulemaking.

3.9.2 *Relevance to Operational (ATS and AOC) Aeronautical Communications*

A trade association, the Worldwide Airline Entertainment Association (WAEA) represents nearly 100 airlines and over 250 airline suppliers and related companies, committed to excellence in in-flight entertainment (IFE), communications and services, and the continual improvement of the airline passenger environment. The use of APC phone service spectrum is a component of overall passenger communications. It is also an arena for new technology insertion by firms in a commercial and competitive arena. Each competitor has grand plans for communications technology insertion, architecture and service expansion. Most involve the concentration of cabin communications on board the aircraft and using the APC spectrum to create a trunk line with the ground. Truck lines that carry several Mbps are envisioned. One application would connect an onboard 802.11 wireless base station with the ground so that passengers could browse the internet from their personal laptops via the wireless LAN. Other applications would connect a cellular picostation with the ground so that passengers could use their personal wireless phones onboard the aircraft. Most of concepts all would utilize advanced technologies such as bandwidth efficient modulation schemes and directional antennas (e.g., onboard phased arrays antennas). While neither this spectral band nor its systems have any direct bearing on operational aeronautical communications, programs that insert new technology in this band may provide a valuable experience base for a modernization program for operational aeronautical communications.

4. Comparative Evaluation of All Candidates

This section is organized as follows:

- 4.1 Review the identified technology candidates and the selected survivors after filtering via a minimum threshold test
- 4.2 Comparative rating of selected survivor candidates under alternative assumptions of values
- 4.3 Summary assessment observations

4.1 Review of the Technology Families

Table 4.1-1 lists all of the identified technology candidates by family. Only a subset of these was selected for evaluation. Many candidates were eliminated from consideration based on the application of minimum threshold test as discussed in section 2.3.3.

Table 4.1-1: Technology Candidates Grouped by Families

	Candidate Solutions
Cellular Telephony Derivatives	TDMA (IS-136), CDMA (IS-95A), CDMAone (IS-95B), CDMA2000 1xRTT, W-CDMA, TD-CDMA, CDMA2000 3x, CDMA2000 1xEV, GSM/GPRS/EDGE, TD-SCDMA, DECT
IEEE 802 Derivatives	IEEE 802.11, IEEE 802.15, IEEE 802.16, IEEE 802.20, ETSI HIPERMAN, ETSI HIPERLAN, ETSI HIPERMAN
Public Safety Radio	APCO P-25 Phase 1, APCO P-25 Phase 2, TETRA Release 1, TETRAPOL, IDRA, IDEN, EDACS, APCO P-34, TETRA Release 2 (TAPS), TETRA Release 2 (TEDS), Project MESA
Satellite and Over the Horizon Communications	HF Data Link, Connexion By Boeing, IGSAGS, SDLS, Thuraya, Inmarsat, Boeing, Sensis, Iridium, Globalstar
Custom Narrowband VHF	VDL Mode 2, VDL Mode 3, VDL Mode 3 w/SAIC, VDL Mode E, VDL Mode 4, E-TDMA
Custom Wideband	ADL, Flash-OFDM, UAT, Mode-S, B-VHF (MC-CDMA)
Military Communications	Link 16, SINCGARS, EPLRS, HAVEQUICK, JTRS
APC Telephony	Airphone, AirCell, and SkyWay systems

The selections and rationale for each of the families is documented in following tables.

Table 4.1-2 summarizes the rationale selection of 2G/3G/4G candidates for evaluation. Note that four candidates were selected for evaluation. For simplicity, WCDMA and CDMA2000 were evaluated as a unit because their general characteristics are quite similar. Together they are designated as WCDMA.

Table 4.1-2: Rationale for Selection of 2G/3G/4G Candidate Solutions

System	Evaluate	Rationale
2G/2.5G Systems		
TDMA (IS-136)	No	Becoming obsolete
CDMA (IS-95A)	No	Superseded by more advanced evolution of this basic technology
CDMAone (IS-95B)	No	Superseded by more advanced evolution of this basic technology
CDMA2000 1xRTT	No	Element of a proposal to ACP; superseded by more advanced evolution (1x EV) of this basic technology
3G Systems		
IMT DS/WCDMA	Yes	Element of a proposal to ICAO ACP; designed for wide area access and support of large macro cells.
IMT TD/TD-CDMA	No	Designed primarily for high user density local area access in context of small macro, micro, and pico cells; offers no value over TD-SCDMA, which has a very similar design
IMT MC/CDMA2000 1x EV	Yes	The 1.25 MHz bandwidth may be more easily accommodated by constraints of available spectrum.
IMT MC/CDMA2000 3x	No	Provides no added value over the combination of WCDMA and CDMA2000 1x EV
IMT SC/GSM/GPRS/EDGE	Yes	Most successful cellular communications system to date; additionally, its relatively narrow 200 kHz bandwidth provides a unique value where the spectrum constraints may prohibit the use of wideband signals
IMT FT/TD-SCDMA	Yes	Of all the time duplex systems, this is the most applicable to the aeronautical environment because it allows for full network coverage over macro cells, micro cells, and pico cells
ITM FT/DECT	No	Supports only very small cells; offers nothing over TD-SCDMA.
4G Systems		
TBD	No	Still being defined so its parameters are not sufficiently established to evaluate.

Table 4.1-3 summarizes the rationale for selection of 802.xx candidates for evaluation. Note that as discussed in section 3, the 802.11 and 802.16 standards supplement each other and are considered as a single candidate that is designated as 802.16.

Table 4.1-3: Rationale for Selection of IEEE 802.xx Candidate Solutions

System	Evaluate	Rationale
IEEE 802.11a) g)	Yes	This is a proposal to the ICAO ACP and is already being implemented to provide AOC communications <i>at the gate</i> and in localized surface areas. Because of the limited range of the 802.11 standard, however, it is considered as a supplement to 802.16(e), and not as a stand-alone candidate
IEEE 802.15	No	Short range limits the applicability to <i>at the gate</i> communications, and does not offer any needed value beyond that offered by 802.11(a).
IEEE 802.16	Yes	This is a proposal to the ICAO ACP and it provides significant performance benefits over 802.11(a), particularly in the areas of QoS, achievable range, and mobility support. 802.16e is a particularly important element of the standard because it supports mobility
IEEE 802.20	No	This standard is not mature. While it aims to provide better mobility support than 802.16(e), if successful, it is likely that 802.20 capabilities will be absorbed by 802.16(e).
ETSI HiperPAN	No	Short range limits the applicability to <i>at the gate</i> communications, and does not offer any needed value beyond that offered by 802.11.
ETSI HiperLAN	No	Comparable technology and performance with 802.11, but with limited market success to date; provides little benefit beyond 802.11 although its MAC is considered superior to the 802.11 CSMA/CA MAC in providing QoS; however, 802.11 evolution is incorporating some of the attractive features of HiperLAN and 802.16e provides a more capable MAC than HiperLAN; thus consideration of HiperLAN adds no additional value over that provided by 802.11 and 802.16e.
ETSI HiperMAN	No	Comparable technology to (and performance of) 802.16. HIPERMAN has adopted 802.16 as its initial baseline, thus HIPERMAN provides no value beyond that offered by 802.16e.

Table 4.1-1 summarizes the rationale selection of public safety radio candidates for evaluation.

Table 4.1-1: Rationale for Selection of Public Safety Radio Candidate Solutions

System	Evaluate	Rationale
Narrow Band Systems		
APCO P25 Phase 1	Yes	Mature technology that offers voice and data services that seem commensurate with the needs of A/G communications. 12.5 kHz channels would seem to offer capacity increase over current system.
APCO P25 Phase 2	No	This is a member of a class of systems that was eliminated from further consideration (Public Safety Radio—Narrowband—TDMA class) because the FDMA class was deemed more likely amenable to the communications problem, and because a custom development system (VDL Mode 3) essentially meets the classification parameters (VDL Mode 3 is a comparable system to the other members of the Public Safety Radio—Narrowband—TDMA class), provides substantially better capability, and was already being evaluated.
TETRA Release 1	No	This is a member of a class of systems that was eliminated from further consideration (Public Safety Radio—Narrowband—TDMA class) because the FDMA class was deemed more likely amenable to the communications problem, and because a custom development system (VDL Mode 3) essentially meets the classification parameters (VDL Mode 3 is a comparable system to the other members of the Public Safety Radio—Narrowband—TDMA class), provides substantially better capability, and was already being evaluated.
TETRAPOL	No	This is a part of the closely grouped set of Narrowband FDMA technologies (P25, TETRAPOL and EDACS). As discussed in section 3.4.2.1, P25 was evaluated as a representative member of this set.
IDRA	No	This is a member of a class of systems that was eliminated from further consideration (Public Safety Radio—Narrowband—TDMA class) because the FDMA class was deemed more likely amenable to the communications problem, and because a custom development system (VDL Mode 3) essentially meets the classification parameters (VDL Mode 3 is a comparable system to the other members of the Public Safety Radio—Narrowband—TDMA class), provides substantially better capability, and was already being evaluated.
iDEN™	No	This is a member of a class of systems that was eliminated from further consideration (Public Safety Radio—Narrowband—TDMA class) because the FDMA class was deemed more likely amenable to the communications problem, and because a custom development system (VDL Mode 3) essentially meets the classification parameters (VDL Mode 3 is a comparable system to the other members of the Public Safety Radio—Narrowband—TDMA class), provides substantially better capability, and was already being evaluated.
EDACS	No	This is a part of the closely grouped set of Narrowband FDMA technologies (P25, TETRAPOL and EDACS). As discussed in section 3.4.2.1, P25 was evaluated as a representative member of this set.
Wide-Band Systems		
APCO P34	Yes	Mature, robust data technology. TDMA guard bands are long, and MAC employs timing advance mechanisms. Scaleable physical layer and robust MAC layer.
Tetra Release 2—TAPS	No	Does not provide any known advantages over P34, and has a very small design range when compared to P34. P34 was selected for analysis as the most suitable technology in this class of technologies.
Tetra Release 2—TEDS	No	Does not provide any known advantages over P34, and has a very small design range when compared to P34. P34 was selected for analysis as the most suitable technology in this class of technologies.
Broad-Band Systems		
Project MESA	No	Project MESA is specifying requirements and identifying candidate technologies—standards not started. System is being designed to provide large data rates in small cells for incident specific applications. It is intended to supplement P25 and P34 networks, not replace them. Might provide a useful airport surface system, but insufficient detail is currently available to analyze the system.

Table 4.1-5 summarizes the rationale for selection of satellite and other over horizon candidates for evaluation.

Table 4.1-5: Rationale for Selection of Satellite Candidate Solutions

System	Evaluate	Rationale
HF Radio		
HF Data Link	No ¹⁰⁴	This is a currently operational system that provides low rate data to remote regions. It is clearly not the future system, as it provides no mechanism to relieve spectrum congestion in the VHF Band, a primary driver for the specification of the Future Aeronautical Communications System. The HF Data Link will have a role in providing aeronautical communications for some time, and roadmaps showing the implementation of the future system should show the HF Data Link as a component of the current system.
Systems Operating in Non-protected Spectrum		
Connexion by Boeing	No	This system operates as a secondary user in a non-AMS(R)S band. Had it been evaluated, it would have merited a score similar to AeroBGAN. While CBB offers a higher data rate than Aero-BGAN, Aero-BGAN operates in an AMS(R)S band that provides priority and pre-emption to aeronautical services. Since the rate provided by BGAN was deemed sufficient to provide the services that can be provided by satellite systems, the difference between the two systems does not impact their score.
CAA Provided Systems		
IGSAGS	No	The described system is conceptual, and has not reached a sufficient level of maturity to believe that it could be implemented in the study time frame.
SDLS	Yes	This system has been designed and specified to provide ATS and AOC A/G communications. The difference between this system and the IGSAGS is that a fairly significant amount of system engineering has been conducted developing the requirements for SDLS, specifying the air interface, and developing a prototype system for demonstration purposes. It is at a much higher level of maturity as a consequence, and was evaluated as a representative member of this branch of the trade tree.
Regional Coverage Systems		
Thuraya	No	System provides regional coverage only (parts of Europe, Africa, and Asia). The air interface does not share commonality with other regional systems, and as such it can not meet the needs of a global interoperable system.
GEO Systems		
Inmarsat	Yes	This system has historically been used for aviation, and has robust and interesting features.
Boeing	No	Ultimate recommendation of GCNSS study was to use Inmarsat satellites. Inmarsat is already being evaluated.
Sensis	No	The described system is conceptual. It utilizes a hybrid physical layer that can be provided by emerging standards and commercial satellites for information broadcast.
LEO/MEO Systems		
Iridium	Yes	Only system that provides truly global coverage. General Aviation avionics exist and are in use.
Globalstar	No	Does not operate in protected spectrum. Does not provide oceanic coverage.

Table 4.1-6 summarizes the rationale for selection of custom narrowband candidates for evaluation.

Table 4.1-6: Rationale for Selection of Custom Narrowband Candidate Solutions

System	Evaluate	Rationale
VDL 2	Yes	This system has been standardized by ICAO and is in use
VDL 3	Yes	This system has been standardized by ICAO and was developed specifically for providing ATC communications in the VHF band.
VDL E	Yes	This technology is a modification of VDL 3. As such, standards development is leveraged, and technical maturity is relatively high. This technology has the additional advantage of (seemingly) being able to transition in 8.33 kHz airspace.
VDL 3 SAIC	Yes	SAIC offers promising utility for VDL 3. By decreasing the frequency reuse distance, the capacity offered by VDL3 should be substantially increased. While this was analyzed, this truly is not a separate technology, but an optional enhancement for VDL 3 and VDL E
VDL 4	Yes	This system has been standardized by ICAO.
E-TDMA	Yes	This system is an alternative to VDL 4 with some similar features

Table 4.1-7 summarizes the rationale for selection of custom broadband candidates for evaluation.

Table 4.1-7: Rationale for Selection Custom Broadband Candidate Solutions

System	Evaluate	Rationale
ADL	Yes	Only custom surface domain candidate
Flash-OFDM	No	Proprietary technology that offers potential; however, the details of the technology are obscure. Other multi-user forms of OFDM that are defined in open literature are under consideration for future aeronautical communications. In evaluating these technologies, a trade of DSS and FH will be conducted.
UAT	Yes	This system is being standardized by ICAO and provides Air-Air broadcast communications
B-VHF	Yes	Promising developmental system

Table 4.1-8 summarizes the rationale for selection of military candidates for evaluation.

Table 4.1-8: Rationale for Selection of Military Candidate Solutions

System	Evaluate	Rationale
JTIDS/MIDS/JRE (Link 16)	Yes	FAA Spectrum engineering indicates that the frequency hopping aspects of this waveform will likely result in mutual interference at a certain loading level (# of emitters present in a particular environment). Use of the waveform in a non-hopping mode is under consideration.
SINCGARS	Yes	This is a narrowband frequency hopper that could provide voice and data within the VHF band
EPLRS	No	This is a data only system.
HAVEQUICK	No	This is a narrowband frequency hopper and will not meet the data needs of the future aeronautical communications
JTRS	No	This is not a waveform. It was discussed here because the modular software architecture and programmable software radio aspects of JTRS are enabling technologies that are applicable to the future communications study

4.2 Comparative Assessment Under Alternative Values Assumptions

4.2.1 Calculation of Composite Candidate Scores

The complete and definitive evaluations of the technology candidates are contained in the summary tables in 3.x.5 Sections that attribute a Red, Yellow or Green for each evaluation criterion. However, In order to support a simple quantitative comparative assessment between the candidates selected for evaluation, the color coded (Red, Yellow, Green) evaluation schema for individual evaluation factors was translated into a numerical score (S_n) by assigning a score of 0 to Red, 1 to Yellow and 2 to Green. Additionally, in order to compute a composite score over all criteria, a weighting scheme is used that allows a weight (W_n) to be applied to each criterion. The composite score is computed as the sum of the $S_n \times W_n$ products for all the criteria as illustrated in table 4.2-1 below.

Table 4.2-1: Evaluation Criteria—Computation of Weighted Scores

General Category	#	Criteria	Scores	Weights	Weighted Scores
Communications Capabilities	1	Meets Voice Needs	S_1	W_1	$S_1 \times W_1$
	2	Meets Basic Datalink Needs	S_2	W_2	$S_2 \times W_2$
	3	Meets Expanded Datalink Needs	S_3	W_3	$S_3 \times W_3$
Maturity for Aeronautical Environment	4	Technology Readiness Level	S_4	W_4	$S_4 \times W_4$
	5	Standardization	S_5	W_5	$S_5 \times W_5$
	6	Certification	S_6	W_6	$S_6 \times W_6$
Cost	7	A/G Communications Infrastructure	S_7	W_7	$S_7 \times W_7$
	8	Avionics	S_8	W_8	$S_8 \times W_8$
Other	10	Spectrum Protection	S_{10}	W_{10}	$S_{10} \times W_{10}$
	11	Security	S_{11}	W_{11}	$S_{11} \times W_{11}$
	12	Transition	S_{12}	W_{12}	$S_{12} \times W_{12}$
		Composite Score		100%	$\Sigma(S_n \times W_n)$

The first three criteria (relating to communications capabilities) in the above table are unique from the other criteria in two ways and this requires some additional explanation.

1) These three communications criteria are applied separately in each of the 5 defined airspace domains: surface, terminal, enroute, oceanic and polar. Thus, for example, a technology can get a good domain specific score in the surface domain, but a poor score in the enroute domain. The rationale for providing a separate score is the recognition that it is not likely that any single candidate will score the best in all airspace domains. Rather, technologies will typically be strong in some domains and weak in others. Accordingly, it was deemed important to capture airspace domain dependent information in order to provide a basis for putting together combinations or hybrid approaches composed of systems that complement each other in the various airspace domains. In addition to the generation of separate scores for each airspace domain, an averaged score over all airspace domains is also calculated by apportioning the weight of the criteria (W_n) among the airspace domains (i.e., defining the set of $\{W_{nD}\}$ where $D = S, T, E, O$ or P denoting the particular airspace domain) such that $\sum W_{nD} = W_n$. This is illustrated in table 4.2-2.

Table 4.2-2: Voice and Data Evaluation: Computing Scores Averaged Over All Airspaces

#	Criteria	Airspace Domain Scores					Airspace Domain Weights					Average Score Over Airspace Domains
		S	T	E	O	P	S	T	E	O	P	
1	Meets Voice Needs	S_{1S}	S_{1T}	S_{1E}	S_{1O}	S_{1P}	W_{1S}	W_{1T}	W_{1E}	W_{1O}	W_{1P}	$\Sigma(S_{1D} \times W_{1D})$
2	Meets Basic Datalink Needs	S_{2S}	S_{2T}	S_{2E}	S_{2O}	S_{2P}	W_{2S}	W_{2T}	W_{2E}	W_{2O}	W_{2P}	$\Sigma(S_{2D} \times W_{2D})$
3	Meets Expanded Datalink Needs	S_{3S}	S_{3T}	S_{3E}	S_{3O}	S_{3P}	W_{3S}	W_{3T}	W_{3E}	W_{3O}	W_{3P}	$\Sigma(S_{3D} \times W_{3D})$

2) Each of the three voice and data criteria is composed of a number of sub-criteria that relate to either functions, capacity or performance. For these three categories, a transformation function is needed to generate a single score from the multiple sub-criteria. In general, this is based upon a formula that adds the scores for functional sub-criteria and multiplies that sum by the scores that relate to capacity and performance. The rationale for this approach is that if a candidate provides the functions, but doesn't meet the capacity and the performance factors, then it does not meet any needs and should be scored as a zero. The specific formulas for computing a criterion score based upon its sub-criteria scores are specified in table 4.2-3, where the f, c, and p, terms refer to the specific functional, capacity and performance sub-criteria of a top-level criteria. Note that the f, c, and p categories were denoted by A, B and C, respectively, in the discussion of evaluation criteria.

Table 4.2-3: Evaluation Criteria: Computation of Voice and Data Scores via Sub-Criteria

#	Criteria	Formula to Compute Criteria Score from Sub-Criteria Scores	Clarification
1	Meets Voice Needs	$\{f1+f2+f3+f4+p1\} \times c1 \times c3 \times p2$	Sub-criteria p1 (mobility management) is properly a functional requirement and is treated so in the formula
2	Meets Basic Datalink Needs	$\{f1+f2\} \times c1 \times c2 \times p1 \times p2$	
3	Meets Expanded Datalink Needs	$(f1+f2) \times c1$	There is no distinct performance sub-criteria for this criteria

4.2.2 Comparison of Composite Scores

Figure 4.2-1 is a bar chart of the composite scores of the candidate technologies averaged across all evaluation criteria and all airspace domains. The set of candidates in this bar chart, and all of the other bar charts in this section, is based upon the candidates that were selected for evaluation (i.e., that passed the minimum threshold test) with the following deviations:

- 25 and 8.33 kHz DSB-AM scores have been added as reference points
- GSM/GPRS/EDGE and TD-SCDMA have been eliminated for simplicity because, with their more limited range, they do not score nearly as well as the two FDD CDMA standards WCDMA and CDMA2000. Also, for simplicity, since these two FDD CDMA systems score essentially identically, they are designated together as simply as WCDMA.
- 802.16 and 802.11 are intended to work complementary with each other and so are together designated as 802.16
- VDL 3 and VDL E are combined in a single entry as VDL 3—this is justified because VDL E is a straightforward modification of VDL 3 and scores only slightly lower

The composite score, averaging over evaluation criteria and airspace domains, was accomplished via the methodology described in the above subsection. The weights used for the different airspace domains and criteria are contained in the inset of figure 4.2-1.

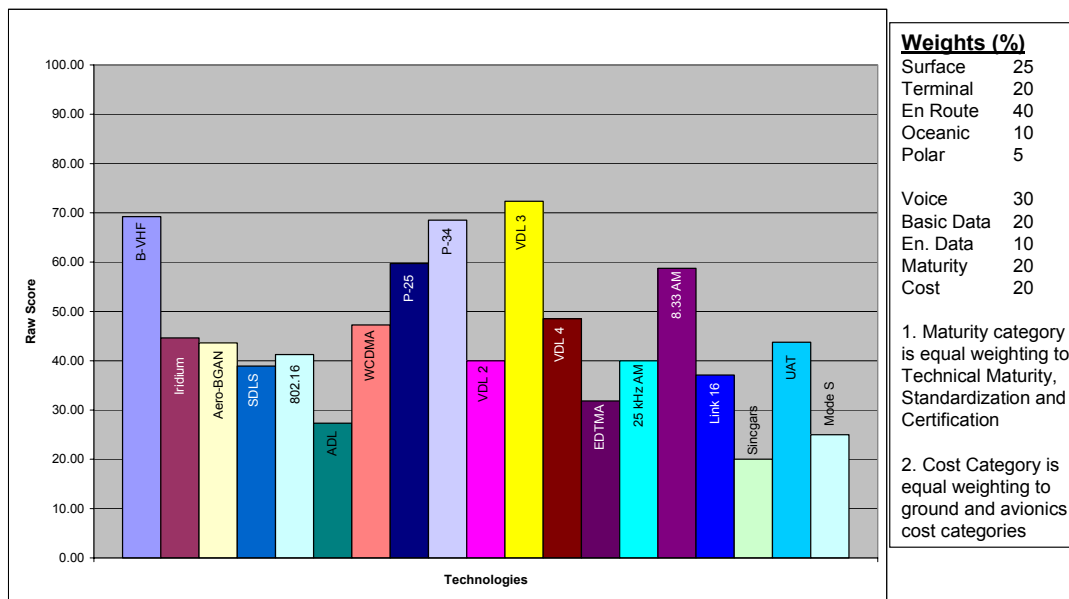


Figure 4.2-1: Composite Evaluation Scores
(Averaged Across All Criteria and Airspace Domains)

Clearly there are 4 technologies that provide both digital voice and data that stand out in that they form a best cluster that all score above 60 (out of 100 maximum). These candidates are B-VHF, P25, P34 and VDL Mode 3. The low scores relative to the maximum of 100 indicate that there is no technology that performs well over all evaluation criteria in all airspace domains, that is mature, and that is estimated to be low cost.

The weights used over the various airspace domains are explicitly summarized in table 4.2-4. Note that the continental airspace was highly valued in that it is allocated 85% of the total weights. Enroute airspace, alone, was given a 40% weight. The weights used were based on judgment, but, as is shown via sensitivity analysis, the set of technology ‘standouts’ are relatively robust to changes in weights.

Table 4.2-4: Chosen Weights for Averaging Over Airspace Domains

Airspace Domain Scores				
Surface	Terminal	Enroute	Oceanic	Polar
W_S	W_T	W_E	W_O	W_P
25%	20%	40%	10%	5%

The weights used to average over the different evaluation criteria are explicitly summarized in table 4.2-5. Note that they place the highest value on communications capabilities: 60% of the weight is in this category. Maturity and cost categories were each rated at 20% and the sub-criteria in each category equally divided up the weight assigned to that category. Spectrum is important, but it served primarily as a minimum threshold criterion: we required that all evaluated candidates be based on aeronautical spectrum. Because of this, spectrum does not serve as a discriminator between candidates, so we assigned it a weight of zero. Security is also important, but because authentication and integrity can always be appropriately provided at the application layer, we judged that the security features were of interest, but should not be weighted. Finally, transition is extremely important, but it serves primarily as a minimum threshold criterion in that if a candidate cannot support a transition, it is eliminated. Thus, we applied a zero weight to transition.

Table 4.2-5: Chosen Weights for Averaging Over Evaluation Criteria

General Category	Criteria	Weights	Value
Communications Capabilities	Meets Voice Needs	W_1	30%
	Meets Basic Data link Needs	W_2	20%
	Meets Expanded Data link Needs	W_3	10%
Maturity for Aeronautical Environment	Technology Readiness Level	W_4	20%
	Standardization	W_5	
	Certification	W_6	
Cost	A/G Communications Infrastructure	W_7	20%
	Avionics	W_8	
Other	Spectrum Protection	W_{10}	0%
	Security	W_{11}	0%
	Transition	W_{12}	0%

4.2.3 Sensitivity Analysis

The sensitivity analysis presented in this subsection is important because it identifies the reasons that candidates score among the best. In addition, it identifies technologies that score well in specific airspace domains or specific evaluation criteria and thus ensure that the initial set of weights used did not eliminate any technology candidates that have a potential for providing significant value to aeronautical communications.

4.2.3.1 Sensitivity to Evaluation Criteria

Many different sets of weights were applied to the evaluation criteria and it was found that the set of best candidates are not very sensitive to modest changes. The most fruitful approach was the application of all of the weight to a specific group of criteria. The specific cases present here are as follows:

- Case 1: Ability to meet voice needs—100 % weight assigned to voice capability criterion
- Case 2: Ability to meet basic data needs—100% weight assigned to basic data criterion
- Case 3: Ability to meet expanded data needs—100% weight assigned to expanded data criterion
- Case 4: Maturity: TRL/standardization/certification—100% weight assigned to maturity category
- Case 5: Cost: service provider infrastructure and avionics—100% weight assigned to cost category

Figure 4.2-2 shows the scores in accord with Case 1 where the ability to provide voice is given all of the weight. Note that the best set of this evaluation is a subset of the best set of the composite evaluation: the P34 candidate does not make the best set here because it was designed primarily as a data system and its ability to support responsive and low latency voice needs to be demonstrated. Because of this, it was graded conservatively on voice and so does not score well. It is also interesting to note that mature systems for aeronautical communications, VDL Mode 3 and 8.33 AM, score the least well of the best set solely because of their lack of support for addressed voice service.

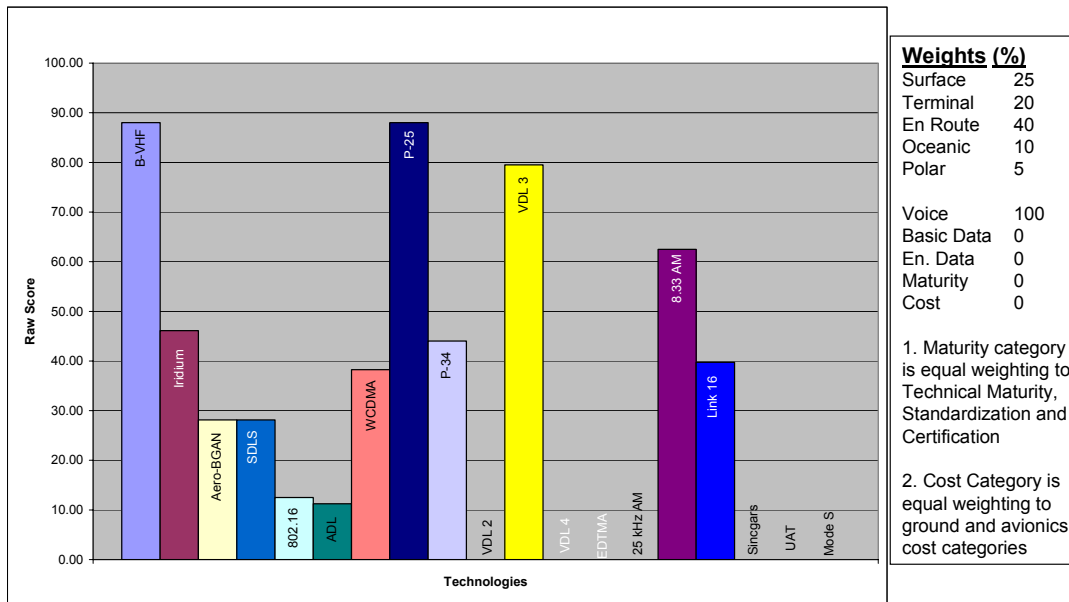


Figure 4.2-2: Score Based on Ability to Meet Voice Needs
(Averaged Across All Airspace Domains)

Figure 4.2-3 shows the scores in accord with Case 2 where the ability to provide basic data is given all of the weight. What is most significant is that two new systems (Aero-BGAN and WCDMA) pop up into the best cluster, while P25 falls out of this cluster. Thus, if basic data is a highly valued capability, then Aero-BGAN and WCDMA may be valuable technologies for aeronautical communications. It is important to note, however, that while the Aero-BGAN service supports the basic data function, its architecture has only a single satellite providing service to most of CONUS. This results in low service availability so that Aero-BGAN is unacceptable for CONUS airspaces. Another issue is that all ground stations for feeder and telemetry links to Aero-BGAN are outside U.S. territory.

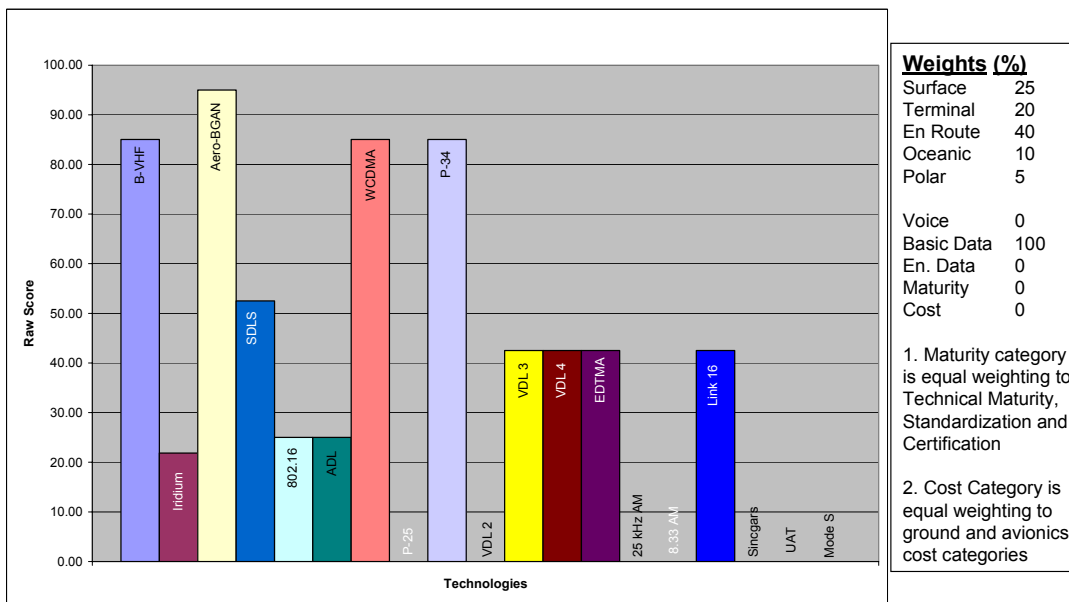


Figure 4.2-3: Score Based on Ability to Meet Basic Data Needs
(Averaged Across All Airspace Domains)

Figure 4.2-4 shows the scores in accord with Case 3 where the ability to provide expanded air-air data is given all of the weight. Two candidates are in the best cluster: (B-VHF, P34) while three others provide some lesser value (Link 16, UAT, Mode S).

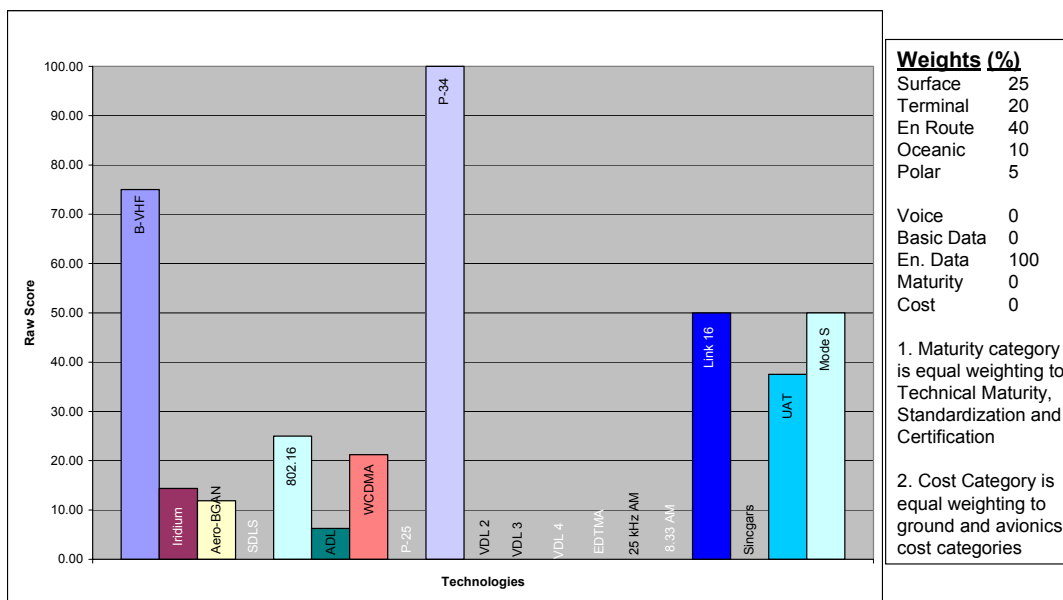


Figure 4.2-4: Score Based on Ability to Meet Expanded Data Needs
(Averaged Across All Airspace Domains)

Figure 4.2-5 shows the score in accord with Case 4 where maturity (TRL, standardization, certification) in the civil aeronautical arena is all important. This demonstrates that maturity does not provide a useful discriminator, since the most mature systems do not score well in meeting the long term requirements.

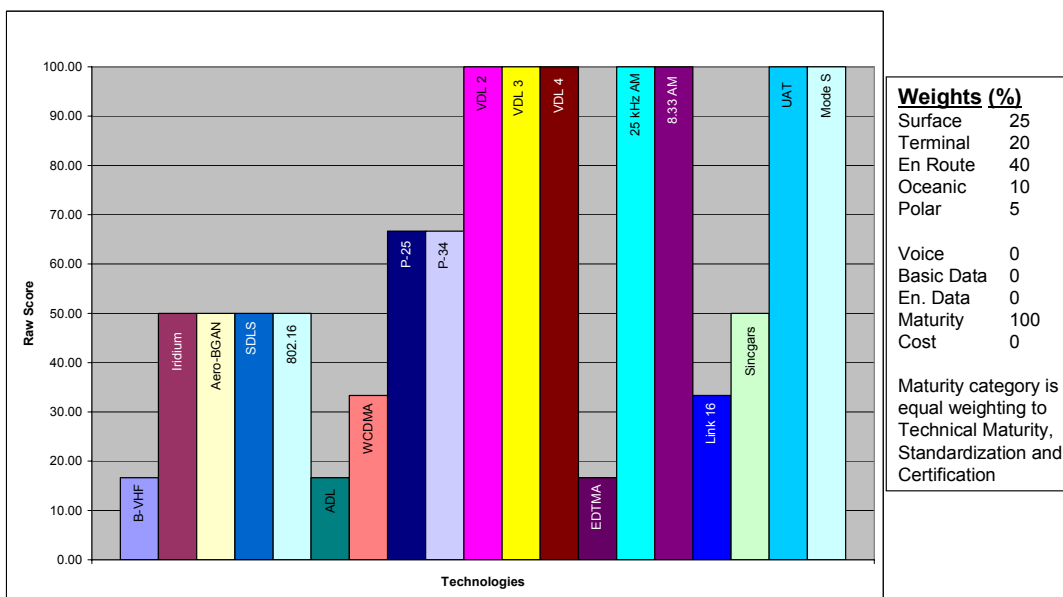


Figure 4.2-5: Score Based on Maturity

Figure 4.2-6 shows the score in accord with Case 5 where cost (Infrastructure and Aircraft) is all important. Note that a long bar indicates low cost. The figure illustrates that cost acts mostly as a negative discriminator by underscoring the systems that are likely to be high cost.

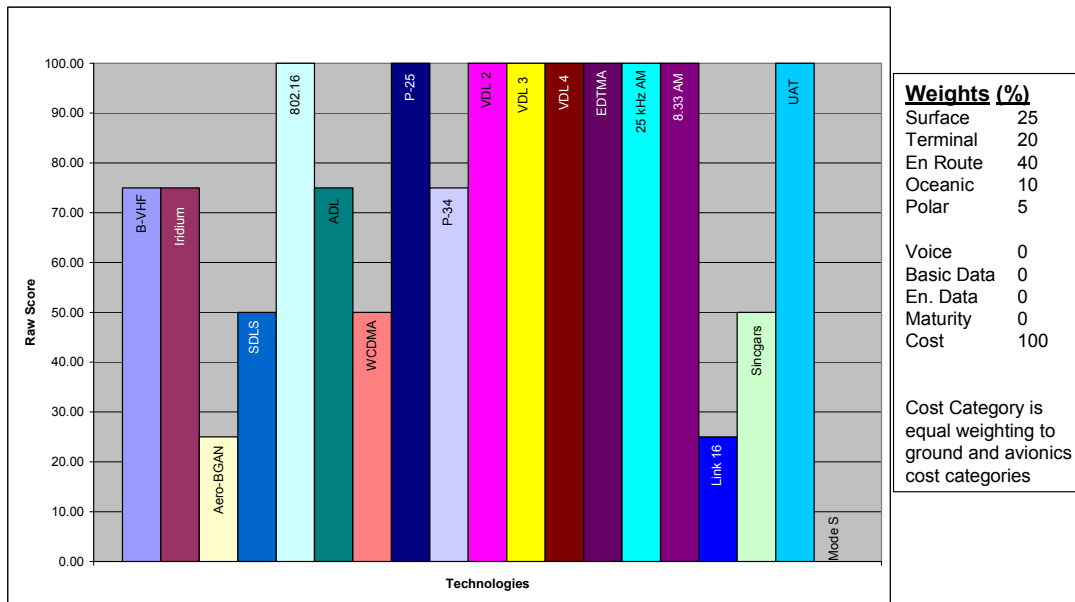


Figure 4.2-6: Score Based on Cost

4.2.3.2 Sensitivity to Airspace Domain

Sensitivity analysis was done to identify additional technologies that could provide value in particular airspace domains. Results are presented here for the surface and oceanic/polar domains. Analysis was also conducted for the enroute and terminal airspace domains, but this did not present a different picture from that of the composite weighted analysis.

Figure 4.2-7 illustrates the scores where all the weight is applied to the surface domain. The evaluation criteria, however, are still weighted in accord with table 4.2-5. What is significant here is that a new technology candidate, 802.16, makes it into the cluster of best candidates.

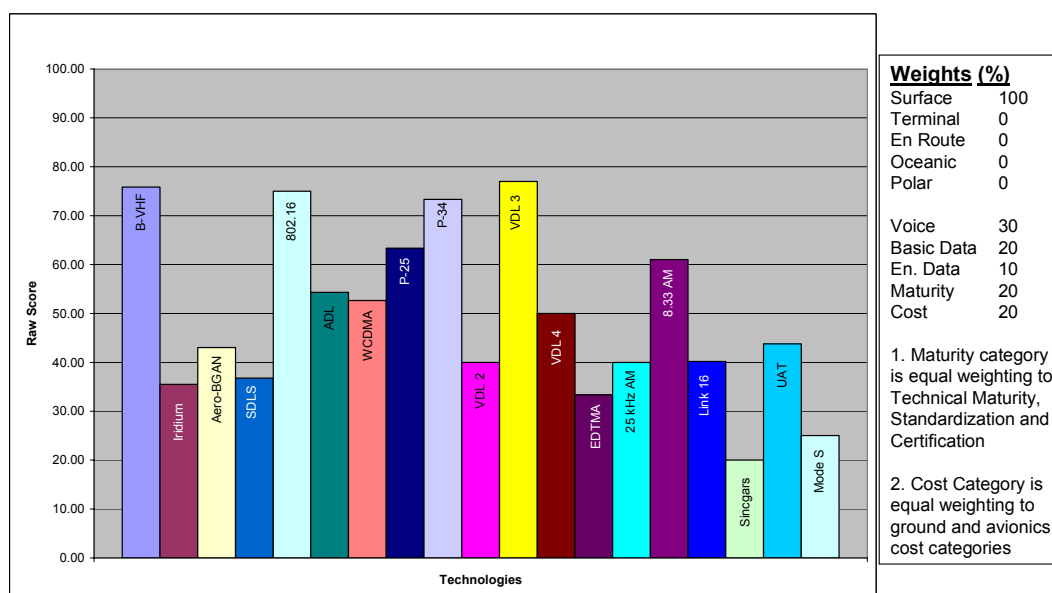


Figure 4.2-7: Score Based On Surface Airspace Domain (Averaged Over All Evaluation Criteria)

Figure 4.2-8 illustrates the scores applicable to the provision of voice and basic data to the oceanic and polar domains. Oceanic and polar regions were weighted in the same ratio (2:1) as in table 4.2-4 above. Similarly, voice and basic data criteria were weighted in the same ratio (1.5:1) as in table 4.2-5 above. It is not surprising that the satellite solutions provide the best solutions in this arena. All three solutions score essentially the same. This is in part because Iridium's service is less capable than Aero-BGAN and SDLS, but this is compensated by the fact that it provides service to both polar as well as oceanic regions.

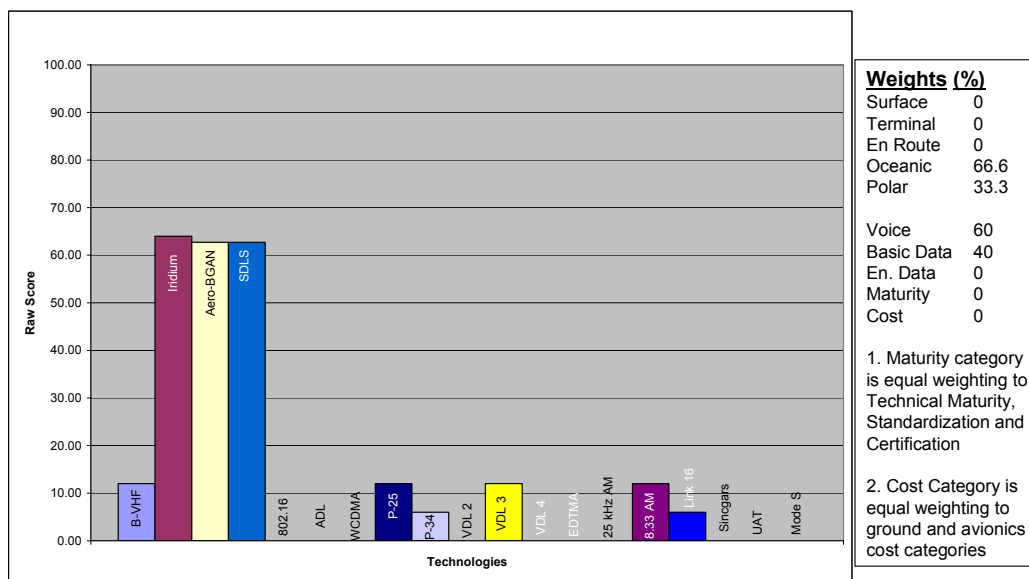


Figure 4.2-8: Score in the Oceanic and Polar Airspace Domains (Averaged Over Voice and Basic Data Capabilities)

4.3 Summary of Analysis Observations

Table 4.3-1 presents a summary of all the technology candidates that were identified to be among the best in the above subsection. The following observations can be made:

Four technologies stand out over the range of evaluation criteria and airspace domains. These are

- B-VHF
- P25
- P34
- VDL Mode 3

Emphasis on the surface airspace domain adds another COTS technology into the mix:

- IEEE 802.16

Emphasis on oceanic and polar airspace domains add satellite solutions

- Aero-BGAN is under construction
- Iridium
- SDLS

If the basic data criterion is emphasized an additional technology offers potential value:

- WCDMA

Finally, if expanded data is emphasized, the candidates that support high data rate air-air communications are selected. This set includes P34 and B-VHF, which are part of the overall best set, but also includes UAT, Mode S and Link 16.

Table 4.3-1: Summary of Best Candidates in Accord with Evaluation Criteria

Technology Candidates	All Evaluation Criteria	Voice	Basic Data	Expanded Data	Surface	Oceanic/ Polar	Most Applicable Spectrum
WCDMA			•				DME
802.16					•		MLS
P34	•		•	•	•		DME
P25	•	•					VHF
Aero-BGAN			•			•	SAT
Iridium						•	SAT
SDLS						•	SAT
VDL 3/VDL E	•	•			•		VHF
B-VHF	•	•	•	•	•		DME
UAT				•			DME
Link16				•			DME
Mode S				•			DME

Other significant observations are as follows:

- Good data solutions and good voice solutions have only one intersection, B-VHF, and that system is developmental. P34 has the potential to provide good voice service, but more analysis is required
- Of the best solutions, the DME band is the most applicable spectrum: 6 of the candidates are most suited to DME spectrum: WCDMA, P34, B-VHF, Mode S, UAT and Link 16
- 2 candidates are most suited to VHF spectrum: P25, VDL 3/VDL E
- 1 candidate is most suited to MLS spectrum: 802.16

5. Translating Analysis Into Pre-Screening Decisions

5.1 Review of the Roadmap for Future Aeronautical Communications

Pre-screening decisions are made in the context of the roadmap defined by available and potentially available spectrum illustrated in figure 5.1-1. In this section, the summary analysis observations presented in section 4 are translated into pre-screening decisions in the context of this roadmap. Accordingly, the subsections below address, in order, the four ‘Future Options’ paths defined by different bands of the aeronautical spectrum. In these discussions two key questions are addressed for each technology:

- Does this technology potentially provide ‘The Solution’?
 - Is it among the best for the range of communications capabilities addressing A/G and A/A voice and data over a wide range of airspace domains?
 - Candidates in this category are high priority

- Does this candidate potentially provide ‘A Component’ of ‘The Solution’?
 - Is it among the best for an important subset of the communications capabilities addressing A/G and A/A voice and data over the different airspace domains?

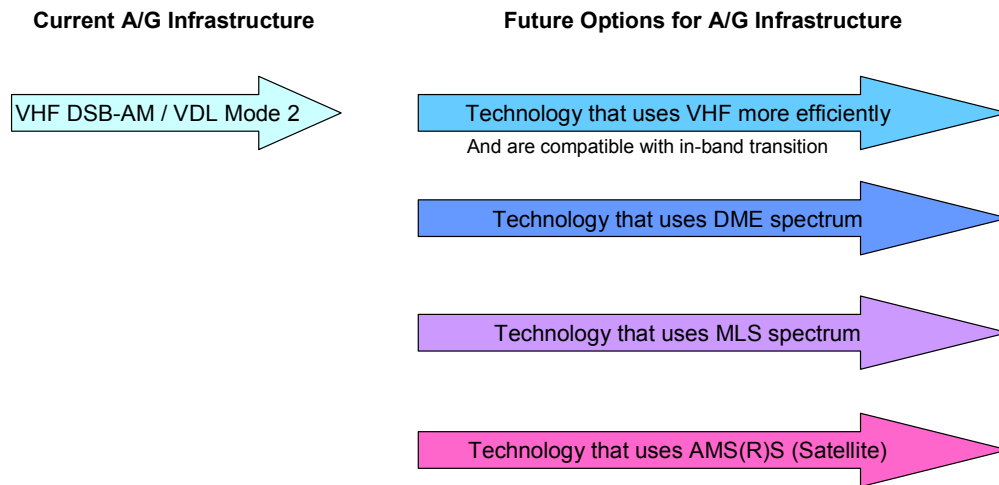


Figure 5.1-1: Roadmap for Future Aeronautical Communications

5.2 Efficient Technologies That Support Transition in VHF Band

The current use of the aeronautical VHF band is dominated by DSB-AM voice communications. A portion of the band is allocated for AOC communications and VDL 2 will increasingly support this role. The major issue for this band is the increasing congestion in the U.S. and Europe. Any candidate technology must be able to relieve that congestion and support a practical transition in its implementation.

The evaluated systems that scored well and are applicable to the VHF band are B-VHF, VDL 3/VDL E, P25, and 8.33 kHz DSB-AM. Table 5.2-1 illustrates the top-level analysis results for these systems. Conclusions about each candidate are made below.

Table 5.2-1: Summary of Best Candidates for VHF Spectrum

Technology Candidates	All Evaluation Criteria	Voice	Basic Data	Expanded Data
P25	•	•		
VDL 3/VDL E	•	•		
B-VHF	•	•	•	•
8.33 kHz DSB-AM		•		

P25

Table 5.2-1 indicates that P25 may be a component of a solution in that it is among the best averaged over all categories and in the voice category in particular. P25 is also attractive since it is a standard that will be widely used in U.S. government wireless networks for the foreseeable future. Additionally, the services and paradigm of P25 appears to be closely allied to that of aeronautical communications so it may provide a useful model for future aeronautical communications development. However, while it does support a large increase in voice channel capacity, its ability to provide data falls well short of future anticipated needs so that it cannot provide a complete solution. P25, with its 12.5 kHz channelization, is

compatible with transition in regions with 25 kHz (or greater) DSB-AM channelization. However, it is not compatible with transition in regions with 8.33 kHz channelization. Because of its low data capacity, P25 is not recommended for future study in the VHF band as a component of the future global communications system.

VDL 3/VDL E

Table 5.2-1 indicates that VDL 3/VDL E may be a component of a solution in that it is among the best averaged over all categories and in the voice category as well. It is also a mature solution so that its risk is low. However, its ability to provide data falls short of future anticipated needs embodied in the evaluation criteria so that it cannot provide a complete solution. VDL 3, with its 25 kHz channelization, is compatible with transition in regions with 25 kHz (or greater) DSB-AM channelization, while VDL E, with its 8.33 kHz channelization, is compatible with transition in regions with 8.33 or 25 kHz DSB-AM channelization. However, such compatibility does not mean that it can be transitioned in congested spectrum because VDL3 compatibility with AM voice and VDL2/ACARS requires different (and more restrictive) frequency planning criteria. VDL 3 and VDL E are recommended for future study in the VHF band, but as the ICOCR/FCOCR data requirements become firm, the ability of VDL 3/VDL E to meet these should be reassessed

B-VHF

Table 5.2-1 illustrates that only B-VHF scores well across a broad range of criteria so it alone is the only candidate that potentially qualifies as ‘The Solution.’ However, it should be underscored that it is an immature system in an early stage of development and that its transition ability in the VHF band is questionable. Furthermore, it is not clear that there is sufficient spectrum in the VHF band to meet future system wide voice and data communications requirements. While implementation of B-VHF in the VHF band may be considered as a component of a solution, the uncertainty over its ability to support an in-band transition remains a problem. B-VHF is not recommended for future study as a candidate for implementation in the VHF band as long as its ability to support transition is in question.

8.33 DSB-AM

Table 5.2-1 indicates the obvious fact that 8.33 kHz DSB-AM addresses the need for increased voice capacity relative to 25 kHz DSB-AM. Thus, 8.33 kHz is a practical solution for congestion in regions with 25 kHz channelization.

Other VHF Technologies: VDL 2/VDL 4/E-TDMA

VDL 2/VDL 4/E-TDMA are not recommended for future study as a component of the future global communications system for 2030 and beyond. Analysis indicates that none of these are a component of the long-term communications solution because they do not score among the best in any category. Furthermore, it is clear that allocation of spectrum to these technologies to provide a data link competes with the demands for voice in an already crowded spectrum band. However, VDL 2, which is already implemented by private service providers in a dedicated portion of the spectrum, will provide an important data link capability prior to the implementation of a future system.

Summary Recommendations for the VHF Band

Because of the need for a practical transition, only one candidate (VDL 3/VDL E) is recommended for the VHF band, and this may not be consistent with transition in the most congested regions of Europe. Furthermore, this technology also does not support the projected data link needs in accord with the data link requirements of the evaluation criteria. In conclusion, it does not appear likely any technology candidate in the VHF band will provide a complete solution for both voice and data, even in continental airspaces. In summation:

- B-VHF, VDL 3/VDL E, and P25 address both voice and data needs; however
 - P25 data capacity is insufficient in target timeframe
 - B-VHF in-band transition is speculative and it is not clear that there is sufficient spectrum in the VHF band to meet all needs in the target timeframe
 - VDL 3/VDL E data capacity is likely to be insufficient in target timeframe (in accord with evaluation criteria)
- Recommendation:
 - VDL 3/VDL E is the only candidate that should be considered for this band
 - As the ICOCR/FCOCR data requirements become firm, the ability of VDL 3/VDL E to meet these should be reassessed

5.3 Technologies That Use DME Spectrum

The DME band potentially offers a large spectral region (960 to 1024 MHz) to support future aeronautical communications systems. This spectrum represents an opportunity to substantially achieve the objectives for the future global communications system. The data objectives are of paramount importance since, as concluded above, there appears to be no candidates in the VHF band that can both support transition and can fully support future aeronautical data link needs. Hence, if the data link needs will not be met in the VHF band, then they must be met in the DME or other band. By this logic, we conclude that a system should not be explored in the DME band unless it has the potential to meet all basic data needs at a minimum.

The evaluated systems that are applicable to the DME band include P34, VDL 3/VDL E, B-VHF, WCDMA, Link 16 and UAT. Table 5.3-1 illustrates the top-level analysis results for these systems. Conclusions about each candidate are made below.

Table 5.3-1: Summary of Best Candidates for DME Spectrum

Technology Candidates	All Evaluation Criteria	Voice	Basic Data	Expanded Data
P34	•		•	•
VDL 3	•	•		
B-VHF	•	•	•	•
WCDMA			•	
Link16				•
Mode S				•
UAT				•

P34

Table 5.3-1 indicates that P34 scores well across a broad range of criteria so it may potentially qualify as ‘The Solution.’ P34 is a COTS solution that may need tailoring for aviation applications. Tailoring requires detailed understanding of the capabilities and limitations of the standard. Active involvement in the standards body to shape future development to aviation needs may also be desirable. Voice is the only area where P34 is not among the best solutions. If voice via P34 packet data service can be shown to be responsive, it may also provide a good voice solution. In any case, P34 provides substantial value as a fully capable data link to augment a voice capability in the VHF band. P34 is recommended for future study of implementations in the DME band in support of communications in the surface, terminal, and enroute domains, and in support of direct air-air communications in all airspace domains

VDL 3

Table 5.3-1 indicates that VDL3 does not support the needed capabilities for a future data link. Accordingly, we do not recommend VDL 3/ VDL E as candidates for future study of implementations in the DME band unless its physical layer is modified to support an increased data rate.

B-VHF

Table 5.3-1 illustrates that the B-VHF candidate scores well across a broad range of criteria so it may potentially qualify as ‘The Solution.’ However, it is important to realize that it is an immature system in an early stage of development. B-VHF is being developed by a consortium of limited membership. If the B-VHF development cannot be brought into the open as part of a global international standardization effort, the solution set should be augmented with such an open standardization approach. Nevertheless, B-VHF is recommended as a candidate for future study of implementations in the DME band in support of communications in the surface, terminal, and enroute domains, and in support of direct air-air communications in all airspace domains

WCDMA

Table 5.3-1 illustrates that WCDMA scores well only for basic data so it may be a component of ‘The Solution.’ However, if its ability to provide voice via its packet data service can be shown to be responsive, it may also provide a good voice solution. It is also important to note that WCDMA does not support direct air-air voice or data either and so has no possibility of supporting ADS-B communications or other concepts where aircraft operate independent of ground infrastructure. In any case, since WCDMA may be a component of a global solution, it is recommended as a secondary candidate for future study of implementations in the DME band in support of communications in the surface, terminal, and enroute domains.

Link16

Table 5.3-1 illustrates that Link16 scores well only for expanded data. Its data latency is inherently somewhat high because of a 6 second look-ahead reservation schedule. In addition, since it was designed for jamming resistance, it does not use spectrum efficiently so that it does not provide for a notional doubling of voice capacity. This would also limit its system wide capacity for data transport. Furthermore, much information about Link16 is secret so that the transfer of technology to civilian use is fraught with risk and uncertainty. Accordingly, Link16 is not recommended as a candidate for future study of implementations in the DME band.

UAT and Mode S

Table 5.3-1 illustrates that UAT and Mode S score among the best only for expanded data, and then primarily for their ability to support ADS-B for which they were designed. Their support for basic data QoS is limited and they have no ability to support voice. UAT and Mode S are not recommended for study as a *communications system candidate* for future aeronautical communications. This statement, however, does not discount their value as components of a surveillance system.

Summary Recommendations for the DME Band

Reallocation of the DME Spectrum to co-primary AM(R)S, (if successful) at the 2007 WARC provides an opportunity to support envisioned aeronautical communications needs across enroute, terminal and surface airspace domains. This (essentially) new spectrum for communications requires careful planning of frequency management criteria and channelization. Selecting a channel spacing that does not accommodate the stated goals of at least 280 kbps for Enhanced Data capacity (Yellow) is not recommended. In summation:

- B-VHF, P34 and VDL 3 are the primary technology solutions recommended for the DME band
 - B-VHF is being developed by a consortium of limited membership: if B-VHF development cannot be brought into the open as part of an international effort, the solution set should be augmented with another custom approach

- P34 is a COTS solution that may need tailoring for aviation applications
- VDL 3 is recommended for the DME band only with a modified physical layer to provide more data capacity
- WCDMA is a secondary solution recommended for the DME band

Of the four candidates identified as having sufficient potential value for implementation in the DME band, two are COTS technologies, which may ultimately prove difficult to adapt to the aeronautical environment, while a third (B-VHF) is in an early stage of development by a consortium of limited membership. The only mature solution in the aeronautical environment is VDL 3, but its data rate is not adequate unless it is modified at the physical layer. With the limitations of this set, there is a risk that after extensive study, none of these systems will be applicable to or be able to meet all of the needs and requirements of the future aeronautical communications. Accordingly, an effort should be considered to define an optimized solution for aeronautical communications based upon the reuse of well-known and implemented protocols from both COTS and custom aeronautical technologies. Modern communications systems are structured and built in modular layers, and an attractive solution may be constructed based on the best and most applicable features of P-34, cellular systems, VDL Mode 3, and 802.16. Through such an approach, it may be possible to define a solution on a rapid schedule since its design will be dominated by the reuse of well-studied and implemented protocols. The goal for this should be applicable to communications in the surface, terminal, and enroute domains and direct air-air communications in all airspace domains.

5.4 Technologies That Use MLS Spectrum

Because of the severe omni-omni antenna path loss in the high frequency MLS band, technologies in this band are applied only to the airport surface where the distances are relatively short.

The evaluated systems that are applicable to the MLS band include 802.16, P34, VDL 3/VDL E, ADL and B-VHF.

Table 5.4-1 lists those technologies that scored among the best for surface candidates.¹⁰⁵ All of them but IEEE 802.16 have already been addressed in the discussion of VHF and DME bands. If eventually implemented in bands other than MLS, these other technologies would provide communications support at the surface in these bands. However, if there are surface communications needs not met by these systems in those bands, then these technologies, as well as IEEE 802.16 implemented in the MLS band can meet these needs.

Table 5.4-1: Summary of Best Candidates for MLS Spectrum

Technology Candidates	All Evaluation Criteria	Voice	Basic Data	Expanded Data	Surface
802.16					•
P34	•		•	•	•
VDL 3/VDL E	•	•			•
B-VHF	•	•	•	•	•

IEEE 802.16

IEEE 802.16 is the only technology selected specifically for application in the MLS band; 802.16 provides the opportunity to support a broad scope of communications needs, both data and voice, over the entire airport surface. Some concepts for surface management require substantially higher data rates than

are needed in other airspace domains. Such data rates on the airport surface might not be met by any future system in the VHF or DME bands. Private service providers have already shown interest in the 802.xx family of wireless protocols and the 802.16e design environment is extremely well matched to the aeronautical surface. It is important to note that the business case for implementing 802.16 infrastructure may be driven by factors beyond ATS and AOC communications, and may involve private service providers, including airport authorities. 802.16 is recommended as a candidate for future study of implementations in the MLS band in support of the surface airspace domain.

Summary Recommendations for the MLS Band

- Because of the severe path loss at MLS frequencies, technologies in this band are applied only to the airport surface, where the distances are relatively short
- IEEE 802.16 is recommended for application in the MLS band:
 - Provides the opportunity for a COTS system to support a broad scope of communications needs, both data and voice, over the entire airport surface
 - Particularly applicable if high data rate requirements on the airport surface cannot be met by a future system in the DME band

5.5 Technologies That Use AMS(R)S (Satellite)

The potential value that satellites provide is to augment a terrestrial aeronautical communications infrastructure as follows:

- To provide broadcast information and advisory services to large geographic areas. This use of satellites is well understood, and has successful business models in the television and radio industries that are already penetrating the aeronautical market for entertainment.
- To provide voice and data communications in oceanic and polar regions where there is typically no other alternative that provides the needed capacity and performance.¹⁰⁶
- To provide voice and data coverage to en-route domains with historically sparse aircraft densities where it may be more cost effective.

Table 5.5-1 illustrates the top-level analysis results for the three satellite systems chosen for detailed analysis. Clearly the evaluation criteria have not provided adequate discrimination between these three alternatives to determine the “best” for remote services. Aero-BGAN and SDLS are based on GEO satellites and so do not provide polar coverage, while Iridium, based on a LEO constellation provides both oceanic and polar coverage.

Table 5.5-1: Evaluation Summary and Characteristics of Best Candidates

Technology Candidates	All Evaluation Criteria	Basic Data	Oceanic	Polar
Aero-BGAN		•	•	
Iridium			•	•
SDLS			•	

The primary discriminators between these three systems are outside the evaluation criteria, but rather in the business aspects, and these are summarized in table 5.5-2.

Table 5.5-2: Key Business Aspects of Satellite Systems

Aero-BGAN	Iridium	SDLS
<ul style="list-style-type: none"> • Satellites are going to be launched and service will be offered • AEEC has an avionics definition program • High data rate at high cost for high end users • Low data rate at lower cost is an option 	<ul style="list-style-type: none"> • Iridium is in service and owner has plans to maintain and replenish • Only system with truly global coverage • Low cost avionics • Low data rate 	<p>SDLS is a concept that uses international and regional L-band satellite bandwidth but requires development of a ground infrastructure</p>

Two of the candidates (Aero-BGAN and Iridium) provide the teleservices and bearer services of a single service provider that the ATS provider would utilize. This minimizes the required ground infrastructure architecture since it is limited to a service interface at a point of presence (PoP). The drawback is that they rely on a proprietary interface of a single service vendor. The SDLS service interface is at the satellite where it requires only a leased segment of bandwidth with the required RF characteristics (e.g., EIRP and G/T). The benefit of this is that multiple satellite vendors may be used to provide high service availability, and a single global system can be defined that is supported by multiple international and regional L-band satellite service providers worldwide. The drawback is the cost associated with developing and maintaining an infrastructure of ground stations that interface with the satellites.

Aero-BGAN

While Aero-BGAN is among the best solutions for basic data, its use for sole-source provisioning of en-route communications over the Continental United States is not recommended. It is unlikely that the INMARSAT satellite constellations will provide sufficient redundancy to meet the requirements for critical NAS services. Further, avionics costs are expected to remain too high for applicability to general aviation. Consequently, this technology is likely restricted to the oceanic domain. The FAA and other CAA's should evaluate cost and QoS values (especially RMA parameters) of relevant service offerings for Aero-BGAN as they become available.

Iridium

Iridium is a unique system with its global coverage. Its low equipment cost has already fostered its use to some extent for passenger communications. However, the data rate that it provides is low, and this single provider solution cannot meet the FAA availability requirements for critical NAS services. Regardless, the FAA and other CAA's should continue to evaluate cost and QoS of service provision via Iridium.

SDLS

The SDLS concept has the potential to provide a basis for a diverse, multi-vendor, and global satellite system that augments terrestrial systems for broadcast and remote airspaces. In the U.S., leased bandwidth from the Mobile Satellite Ventures (formerly American Mobile Satellite Corporation) and INMARSAT satellites may be able to meet the availability constraints of NAS critical services, by providing satellites with diverse look angles and an on-orbit spare. This technology, if used in conjunction with a broadband technology where needed may be a good solution for future aeronautical communications.

Summary Recommendations for the Satellite L Band

- Aero-BGAN, Iridium and SDLS can provide coverage in remote regions
 - Ability of any these solutions to meet en-route availability requirements is questionable: e.g., the I-4 constellation provides only single satellite coverage for most areas of the world
 - The focus of the use of these solutions should be in oceanic and polar airspace domains
- Evaluation criteria have not provided adequate discrimination between these three to determine the "best" for remote services
 - In order to identify a common global system that provides communications for remote regions a gap analysis between Aero-BGAN and Iridium service performance vs. DO-270 and NexSat requirements should be performed
 - Should neither service prove acceptable for remote A/G communications, further exploration of the SDLS concept should be conducted

5.6 Summary Conclusions

This section summarizes the recommendations made above. Three core technologies and four supplementary technologies are recommended for further study as indicated in figure 5.6-1.

- Technologies applicable for provision of communications over all continental airspace domains (Enroute, Terminal And Surface)
 - Primary Recommendations
 - P34
 - VDL 3
 - B-VHF
 - Secondary Recommendations
 - WCDMA
- Technologies applicable for provision of communications over specific airspace domains
 - Oceanic:
 - Aero-BGAN
 - Iridium
 - Surface:
 - IEEE 802.16

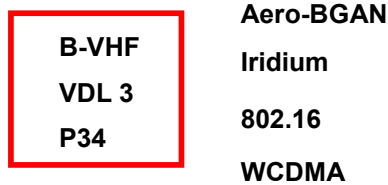


Figure 5.6-1: Technology Recommendations

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Appendix B—Evaluation Criteria and Metrics

ITT and QinetiQ Evaluation Criteria

November, 2004

Version 4

Top Level Assessment of Alternative Candidates—Summary Evaluation

	Candidate Characterization	Allowed Values	Discussion
A	Terrestrial or Space-based	Terrestrial (T), LEO, MEO, GEO	Indicates that the system infrastructure is based on A/G links via ground stations or satellites (and what kind of satellites).
B	Potential Operating Frequency Bands	118 to 137 MHz, 960 to 1024 MHz, 1610 to 1626.5 MHz, 5000 to 5150 MHz, other	Defines the target bands that are appropriate to the candidate; more than one band may be deemed as a potential target.
C	Potential Airspace Coverage	Oceanic (O), Enroute (ER), Terminal (T), Surface (S), Polar (P)	Defines where the candidate <i>could</i> provide coverage (this is distinct from where it <i>should</i> provide coverage); more than one value may be entered
	Candidate Evaluation	Allowed Values	Discussion (See data dictionary for additional discussion)
1	Meets Voice Needs		G, Y, or R status is assigned by judging the ability of candidate meet requirements for voice (see following pages for discussion)
2	Meets Basic Data Link Needs		G, Y, or R status is assigned by judging the ability of candidate meet communications requirements for Basic data; Basic data is defined as that which supports Safety and Regularity of Flight, as defined by ICAO Annex 10.
3	Meets Expanded Data Link Needs		G, Y, or R status is assigned by judging the ability of candidate meet communications requirements for Expanded data; Expanded data includes Air to Air and other requirements in support of very advanced concepts for separation assurance.
4	Technical Readiness Level (TRL)		G, Y, or R status is assigned by assessing the TRL of the proposed candidate.
5	Standardization Status		G, Y, or R status is assigned based upon the existence of applicable standards for the candidate
6	Certifiability		G, Y, or R status is assigned based upon the a complexity assessment of the candidate
7	Cost of Ground Infrastructure		G, Y, or R status is assigned based upon the cost of ground communications infrastructure
8	Cost to Aircraft		G, Y, or R status is assigned based upon the cost of aircraft communications infrastructure
9	[Item Deleted]		
10	Spectrum Protection		G, Y, or R status is assigned based upon the extent to which the potential frequency bands are consistent with aeronautical safety critical communications
11	Security		G, Y, or R status is assigned based upon the extent to which candidate supports authentication, integrity and robustness to jamming
12	Transition		G, Y, or R status is assigned based upon candidate transition characteristics. Factors considered include return on partial investment, ease of technical migration (spectral, physical), and ease of operational migration (air and ground users)

Data Dictionary for Candidate Evaluation Criteria

Item	Sub-Item	Desired Features of a Candidate that are used in the evaluation: G, Y, R status is developed by judging the ability of a candidate to supply the desired features
1: Meets Voice Needs	A. Functional Requirements: Supported Voice Services	<p>1. Pilot-Controller Talk Group: this is essentially the setup and maintenance of a group conference call between a Controller and all of the Pilots in the domain of that Controller. Assessed as: Green—The candidate required no modifications; the candidate has already demonstrated/validated this capability; or, The candidate requires very small and/or low risk modifications. Yellow—The candidate requires moderate modifications in order to meet this criterion. Red—The candidate can not reasonably implement this capability with moderate modification(s).</p> <hr/> <p>2. Pilot-Controller Selective Addressing: supports a call and dialog between a Controller and a selected Pilot that is not overheard by other Pilots Assessed as: Green—The candidate required no modifications; the candidate has already demonstrated/validated this capability; or, The candidate requires very small and/or low risk modifications. Yellow—The candidate requires moderate modifications in order to meet this criterion. Red—The candidate can not reasonably implement this capability with moderate modification(s).</p> <hr/> <p>3. Direct Pilot-Pilot: the candidate allows Pilots to talk directly with each other without requiring other facilities as an intermediary. Assessed as: Green if the candidate is using only aircraft equipment. Yellow if ground or space equipment is required and Red, if the candidate could not do the function.</p> <p>4. Broadcast capability. The technology provides a voice broadcast capability. Assessed as: Green—The candidate requires no modifications; the candidate has already demonstrated/validated this capability; or, The candidate requires very small and/or low risk modifications in order to meet this criterion. Yellow—The candidate requires moderate modifications in order to meet this criterion. Red—The candidate can not reasonably implement this capability with moderate modification(s).</p>
	B. Capacity Requirements	<p>1. Capacity provided: The candidate supports a significant increase in communications capacity. Assessed as: Green—The candidate supports a notional doubling of capacity. Yellow—The candidate supports a moderate increase in capacity. Red—The candidate has, at best, marginally more capacity.</p> <hr/> <p>Note: this is provisional and should be revisited with issuance of ICOCR</p> <hr/> <p>2. [Item Deleted]</p> <hr/> <p>3. Address space. The candidate supports a sufficient number of addressed users per talk group. Assessed as: Green—The candidate supports greater than 200 addressed users per talk group. Note: 200 addressed users based on Chicago surface aircraft number. Yellow—The candidate supports between 30 and 200 addressed users per talk group. Red—The candidate supports less than 30 addressed users per talk group. Note: 30 addressed users based on RTCA DO-290.</p>

Item	Sub-Item	Desired Features of a Candidate that are used in the evaluation: G, Y, R status is developed by judging the ability of a candidate to supply the desired features
1: Meets Voice Needs (continued)	C. Performance Requirements for Pilot Controller Voice Services	<p>1. Aircraft mobility management: should dynamically manage Talk Groups as aircraft members join and leave. The intent of this is that a candidate can add or subtract users without denial of service (to remaining talk group members) and without unacceptable additional controller/pilot workload.</p> <p>Assessed as: Green—The candidate required no modifications; the candidate has already demonstrated/validated this capability; or, The candidate requires very small and/or low risk modifications. Yellow—The candidate requires moderate modifications in order to meet this criterion. Red—The candidate can not reasonably implement this capability with moderate modification(s).</p> <hr/> <p>2. Latency: The candidate should have acceptable one-way end-to-end voice latency</p> <p>Assessed as: Green—Less than or equal to 250 ms one way. Yellow—More than 250 ms and less than 400 ms one way. Red—Greater than or equal to 400 ms one way.</p> <hr/> <p>3. [Item Deleted]</p> <hr/> <p>4. [Item Deleted]</p>
2: Meets Basic Data Link Needs	A. Functional Requirements: Supported Data Services	<p>1. Air-to-Ground and Ground-to-Air Addressed Data Transport</p> <p>Assessed as: Green—The candidate required no modifications; the candidate has already demonstrated/validated this capability; or, The candidate requires very small and/or low risk modifications. Yellow—The candidate requires moderate modifications in order to meet this criterion. Red—The candidate can not reasonably implement this capability with moderate modification(s).</p> <hr/> <p>2. Ground-to-Air Broadcast Data Transport</p> <p>Assessed as: Green—The candidate required no modifications; the candidate has already demonstrated/validated this capability; or, The candidate requires very small and/or low risk modifications. Yellow—The candidate requires moderate modifications in order to meet this criterion. Red—The candidate can not reasonably implement this capability with moderate modification(s).</p> <hr/> <p>3. [Moved to Enhanced Data]</p>
	B. Capacity Requirements	<p>1. Aggregate Data Rate. This criterion assesses the data throughput provided to a user group. The bit rates below are aggregate and include all transmitted bits. The assessment is whether the aggregate data rate to and from aircraft in a user group is acceptable. Should a distinction between average and peak be required (technology specific detail) then the analyst annotation should explain what is being evaluated and why.</p> <p>Assessed as: Green—Greater than or equal to 31.5 kbps per user group (per MACONDO rate estimate). Yellow—Greater than or equal to 2.4 kbps and less than 31.5 kbps per user group. Red—Less than the equivalent of today's VDL service (i.e., less than 2.4 kbps).</p> <hr/> <p>Note: this is provisional and should be revisited with issuance of ICOCR</p> <hr/> <p>2. Number of Users. The number of users that can receive addressed data services in a user group is acceptable.</p> <p>Assessed as: Green—The candidate supports greater than 200 addressed users per user group. Yellow—The candidate supports between 30 and 200 addressed users per user group. Red—The candidate supports less than 30 addressed users per user group.</p>

Item	Sub-Item	Desired Features of a Candidate that are used in the evaluation: G, Y, R status is developed by judging the ability of a candidate to supply the desired features
2: Meets Basic Data Link Needs (continued)	C. Performance Requirements for Data Transport	<p>1. Uplink and Downlink Priority Levels/QoS: service supports priority levels such that traffic at a lower priority does not degrade higher priority traffic beyond its required QoS. Assessed as: Green—The candidate required no modifications; the candidate has already demonstrated/validated this capability; or, The candidate requires very small and/or low risk modifications. Yellow—The candidate requires moderate modifications in order to meet this criterion. Red—The candidate can not reasonably implement this capability with moderate modification(s).</p> <hr/> <p>2. Latency. Be consistent with the end-to-end latency requirements by classes of traffic as specified for ICAO Annex 10, Volume III, Part 1, Chapter 3 covering the ATN (e.g., 4.5 sec at 95% assurance for Class B) Assessed as: Green—Meets ATSC Class B. Yellow—Meets ATSC Class C. Red—Meets ATSC Class D or lower.</p>
3: Meets Expanded Data Link Needs	A. Functional	<p>1. ADS-B. Assessed as: Green—The candidate required no modifications; the candidate has already demonstrated/validated this capability; or, The candidate requires very small and/or low risk modifications. Yellow—The candidate requires moderate modifications in order to meet this criterion. Red—The candidate can not reasonably implement this capability with moderate modification(s).</p> <p>2. Pilot-Pilot Data Transport: the candidate allows Pilots to exchange data with each other. It is not necessary that this function be provided as a direct avionics-to-avionics transport. An intermediary is acceptable when provisioning this service.</p> <p>Assessed as: Green—The candidate required no modifications; the candidate has already demonstrated/validated this capability; or, The candidate requires very small and/or low risk modifications. Yellow—The candidate requires moderate modifications in order to meet this criterion. Red—The candidate can not reasonably implement this capability with moderate modification(s).</p>
	B. Capacity Requirements	<p>1. Aggregate Data Rate. This criterion assesses the data throughput provided to a user group. The bit rates below are aggregate and include all transmitted bits. The assessment is whether the aggregate data rate to and from aircraft in a user group is acceptable. Should a distinction between average and peak be required (technology specific detail) then the analyst annotation should explain what is being evaluated and why. Assessed as: Green—Greater than or equal to 2 Mbps per user group Yellow—Greater than 280 kbps and less than 2 Mbps per user group. Red—Equal to or less than 280 kbps</p> <p>Note: this is provisional and should be revisited with issuance of ICOCR</p>
	C. Performance	1. No performance requirements beyond Basic data

Item	Guide to determining G,Y, R status
4: Technology Readiness Level	<p>[G, Y, or R status is assigned by assessing the TRL of the proposed candidate.] Assessed as: Green is a TRL 6 or above Yellow is TRL 5-4 Red is TRL 3 and below</p>
5: Standardization Status	<p>[G, Y, or R status is assigned based upon the existence of applicable standards for the candidate] Assessed as: Green: candidates that have a publicly available aeronautical standard; Yellow: candidates are supported by a mature commercial standard Red: candidates for which a supporting standard does not exist or is not publicly available</p>

Item	Guide to determining G,Y, R status
6: Certifiability	<p>Measure of certification risk</p> <p>Assessed as: Green: Candidates developed for the aviation industry and either currently certified or known to be in the certification process Yellow: Candidates developed for safety related services (Public safety and the like) but not currently in the aviation certification process Red: All other candidates</p>
7: Ground Infrastructure Cost	<p>Relative cost to replace or upgrade infrastructure with the necessary availability and diversity requirements for critical services, as a replacement to VHF DSB-AM; where applicable, replacement of a ground station covering a large area (e.g., high enroute sector) should be assessed: thus, a candidate not able to project a signal at a large range from a single ground station would require multiple replacement ground stations; this naturally penalizes candidates that cannot practically project a signal at a large range. The evaluation will include any unusual maintenance requirements of a candidate (to include leased services, maintenance of Network Operational Centers, extraordinary Telco bandwidth requirements and the like).</p> <p>Assessed as: Green: low relative cost Yellow: moderate relative cost Red: high relative cost</p>
8: Cost to Aircraft	<p>Relative cost to upgrade avionics with new candidate voice and data link technology but maintain VHF DSB-AM capability;</p> <p>Assessed as: Green: low relative cost Yellow: moderate relative cost Red: high relative cost</p>
9: COTS Leveraging	[Item Deleted]
10: Spectrum Protection	<p>[G, Y, or R status is assigned based upon the extent to which the potential frequency bands are consistent with aeronautical safety critical communications]</p> <p>Assessed as: Green: the target band for the alternative has a global allocation for the Aeronautical Mobile (route) Service (AM(R)S) for ground-based systems or Aeronautical Mobile Satellite (route) Service (AMS(R)S) for satellite-based systems, as applicable Yellow: it can be reasonably expected that an additional global allocation (AM(R)S for terrestrial or AMS(R)S for satellite-based) could be added to the target band or if the band is shared with other aviation systems, it is feasible that appropriate frequency assignment criteria could be developed within ICAO that would prevent interference with the other aviation systems. Red: All other circumstances</p>
11. Security	<p>[G, Y, or R status is assigned based upon the extent to which candidate supports authentication and integrity]</p> <p>Status is assigned based upon the extent to which candidate supports authentication and integrity (A and I) and robustness to jamming.</p> <p>Assessed as: Green: candidate supports A and I Yellow: candidate can be modified to support A and I. Red: candidate cannot be modified to support A and I.</p>
12. Transition	<p>The candidate must have acceptable transition characteristics, including: return on partial investment ease of technical migration (spectral, physical) ease of operational migration (air and ground users)</p> <p>Assessed as: Green candidate:</p> <ul style="list-style-type: none"> provides return on investment (i.e. service provision/benefit) without requiring full/complete investment /deployment, and can be operated simultaneously (in adjacent airspace) with legacy A/G comm. system (i.e. you can bring the new system up incrementally, while bringing the legacy system down incrementally), and initial transition can be nearly operationally transparent (i.e. initially, users do not have to significantly alter procedures) or features that drive changes in operational procedures can be employed incrementally <p>Yellow candidate: can have no attributes of a Red candidate</p> <p>Red candidate:</p> <ul style="list-style-type: none"> provides little or no return on investment (i.e. service provision/benefit) until full/complete investment /deployment, or requires operation of legacy A/G comm. system be widely discontinued in order to operate, or initial transition requires significant changes to operational procedures.

Appendix C—NASA Requests For Information

Introduction:

The Air Traffic communications capacity will be reaching saturation in Europe and the United States. The International Civil Aviation Organization (ICAO) is seeking a common, global solution through the Aeronautical Communications Panel (ACP). The FAA and Eurocontrol have started a study of the problem with the support of NASA. As part of the effort to develop a unique solution, to solve the congestion problem, ITT industries teamed up with NASA to conduct a study and present the results of the study in the form of a report. The study involved researching all the existing technologies within the VHF band as well as Non-VHF band and ascertaining the fit of each technology as a potential candidate technology to be introduced within the 2015 to 2020 time frame. To do this a thorough knowledge and understanding of the individual technology was necessary and hence inputs from the industry proponents of each particular technology were solicited in the form of an RFI. There were two RFI's submitted. The first RFI was for terrestrial based Advanced Air Ground Communications Concepts for Air Traffic Services. The second was for Satellite-based Air Ground Communications Concepts for Air Traffic Services

Description of 1st RFI:

The RFI was issued on June 18th, 2004 and was for information on technologies pertaining to Advanced Air Ground Communications Concepts for Air Traffic Services. The exact description of the RFI is as given below:

THIS IS NOT A NOTICE OF SOLICITATION. IT IS A REQUEST FOR INFORMATION (RFI) ONLY.

In responding to this notice, please refer to “**Advanced Air Ground Communications Concepts for Air Traffic Services.**” Send information/literature/qualification statement no later than **July 19, 2004** to the e-mail or postal address as provided herein. NASA does not intend to award a contract based on this information. This RFI is for planning purposes only and to allow industry the opportunity to provide information relative to the goals set forth below.

NASA Glenn Research Center (GRC) is seeking information about advanced concepts in future air-ground communications systems for potential use in providing air traffic services (ATS). For the purposes of this RFI, ATS includes the following services: separation assurance; air traffic control advisory; traffic management synchronization; navigation; airspace management; emergency and alerting; flight planning; infrastructure/information management; and traffic management strategic flow. Transition to this future system would begin in the 2015 to 2020 time period, and the useful life of the system should be at least 20 to 30 years.

The information received from this RFI will be used by NASA GRC in support of a collaborative Future Communications Study between the Federal Aviation Administration (FAA) and Eurocontrol. The FAA/Eurocontrol Future Communications Study will help to define and design a global air-ground communications system that provides for world-wide interoperability among all ATS users. The work plan and associated terms of reference for the FAA/Eurocontrol Future Communications Study can be found at <http://www.eurocontrol.int/faa-euro/AP-group-meetings/ap17/ap17.htm>

NASA GRC is responsible for Technical Theme 3 in the Future Communications Study work plan, to investigate new technologies for mobile communication. This RFI is intended to provide input for conducting Task 3.1, Technology Pre-screening. The Advanced Engineering and Sciences Division of ITT Industries, Inc. is under contract to assist NASA GRC in the technology pre-screening task. They and

other contractors of NASA and the FAA will have access to the information submitted for the purpose of conducting the technology pre-screening process.

NASA GRC seeks information on candidate system solutions for mobile communications that can be used for ATS both domestically and internationally. Both current capabilities (based on existing or planned products) and potential future concepts are encouraged in response to this RFI. Concepts based on terrestrial broadcast, air-to-air relay, and/or satellite relay are acceptable as inputs to the technology pre-screening process.

It is desirable that information provided to describe the advanced air-ground communications system concepts include:

- A technical description of the system solution including but limited to: air interface; end-to-end latency (pilot-to-controller and controller-to-pilot if asymmetric); ATS communications services provided; protocols; network topology; spectrum required; security features; and any simplifying assumptions needed to meet or exceed the design goals described below.
- Areas of expected improvement over current air-ground communications systems for ATS.
- Scalability of the system to meet increasing demands and the system's ultimate total capacity.
- A description of the impact (high-level transition plan, schedule and relative cost) on current airborne and ground avionics and infrastructure.
- Technical maturity of the system solution, including status of applicable standards, commercial availability of electronics, and estimates of time for infusion into the National Airspace System.

The following high-level functional design goals for a mobile air-ground communications system to be used in providing ATS are intended to provide insight into the performance of the current system, and desired characteristics of a future system:

- Increase the channel capacity of the current air-ground communications system.
- Utilize the VHF aeronautical communications frequency band, or justify the utilization of other aeronautical frequency allocations.
- Provide for an orderly and efficient transition from the current VHF communications system.
- Provide a mechanism for "real-time" voice, with requisite combined performance in latency and channel access that promotes efficient and effective communications between a controller and the set of aircraft within the controlled airspace.
- Provide a mechanism for both addressable and broadcast data functions.
- Provide a mechanism to specify various Quality of Service (QoS) classes for data transfer.
- Within each QoS class, provide a mechanism for scheduling and prioritizing data delivery.
- Include configurable security measures to provide user authentication features.
- Provide a mechanism to control multiple sectors in the same geographic area.
- Provide aircraft position location capability.

Description of Responses:

NASA received 13 RFI responses. The responses have been tabulated as shown below and include details as to whether a particular technology offered a solution and if yes, what the solution was and whether the solution is relevant to the problem at hand. The response also includes information regarding copyrights for the considered technology, whether it is proprietary or for limited use only.

Table 1

Respondent	Proprietary?	Offered a Solution?	Solution	Relevant?
B-12	No – papers provided have been presented to ICAO ACP WGC	Yes	Packet Radio	Yes
Harris	Government use only	Yes	VDL-3	Not a new idea. Already a candidate technology
			VOIP on OFDM in MLS Band	Yes
University Research Foundation Maryland Advanced Development Laboratory Division	Government use only	Yes	Advanced Slotted Ring	No – This is a ground based network communications technology with no defined air interface.
Sensis Corporation and Seagull Technology, Inc.	Yes	Yes	Flash OFDM	Yes, but the details of solution are not presented
			B-VHF	Already being considered
			Smart Antennas	Not a complete solution, rather an enabling technology
Avionics Engineering Center Ohio University	No	No	Mention that CDMA might be a promising technology	Current proposed systems include several CDMA systems
SITA	No	Yes	VDL-2	Already being considered
			IP over VDL-2	Is a component of the VDL-2 solution
			Classic INMARSAT SATCOM	Yes
			Swift64	Yes
			AeroBGAN	Already being considered
Rockwell Collins	No; However paper was copy righted	Yes	VDL Mode E	Yes
Frequentis	Commercial in confidence	Yes	B-VHF	Already being considered
			Safety and Security Enhanced Voice	Yes
Redflex Communications	No	No		
Cisco Systems	No	No		
ITT Industries-ACD and TrellisWare Technologies, Inc	No	Yes	VDL Mode 3 + Single Antenna Interference Cancellation	Yes – Can be used to modify the VDL-3 baseline to provide increased spectrum utilization
General Dynamics	No; Copyrighted paper presented in general literature.	Yes	Iridium Netted Radios	Yes
Raytheon	No	No.		Provided in depth analysis of suitability of TDMA, CDMA, LEO, GEO, Packet Radio and VoIP
Notes 1. General Dynamics response not yet received. Proposed solution assumed to be in line with published paper. 2. Response is still expected from Boeing.				

Description of 2nd RFI:

The RFI was issued on July 26th, 2004 and was for information on Satellite based technologies pertaining to Advanced Air Ground Communications Concepts for Air Traffic Services. The exact description of the RFI is as given below:

THIS IS NOT A NOTICE OF SOLICITATION. IT IS A REQUEST FOR INFORMATION (RFI) ONLY.

In responding to this notice, please refer to “Satellite-based Air Ground Communications Concepts for Air Traffic Services.” Send information/literature/qualification statement no later than August 13, 2004 to the e-mail or postal address as provided herein. NASA does not intend to award a contract based on this information. This RFI is for planning purposes only and to allow industry the opportunity to provide information relative to the goals set forth below.

NASA Glenn Research Center (GRC) is seeking information about advanced concepts that are based on satellite communications for future air-ground communications systems providing air traffic services (ATS). This RFI is closely associated with the RFI NNC04PRA002L that was posted on June 18, 2004 and closed on July 19, 2004. This RFI focuses on concepts specifically related to the use of communications satellites in providing future air-ground communications in any or all aviation flight segments (surface, terminal, en-route and oceanic). For the purposes of this RFI, ATS includes the following services: separation assurance; air traffic control advisory; traffic management synchronization; navigation; airspace management; emergency and alerting; flight planning; infrastructure/information management; and traffic management strategic flow. Transition to this future system would begin in the 2015 to 2020 time period, and the useful life of the system should be at least 20 to 30 years.

The information received from this RFI will be used by NASA GRC in support of a collaborative Future Communications Study between the Federal Aviation Administration (FAA) and Eurocontrol. The FAA/Eurocontrol Future Communications Study will help to define and design a global air-ground communications system that provides for world-wide interoperability among all ATS users. The work plan and associated terms of reference for the FAA/Eurocontrol Future Communications Study can be found at <http://www.eurocontrol.int/faa-euro/AP-group-meetings/ap17/ap17.htm>

NASA GRC is responsible for Technical Theme 3 in the Future Communications Study work plan, to investigate new technologies for mobile communication. This RFI is intended to provide input for conducting Task 3.1, Technology Pre-screening. The Advanced Engineering and Sciences Division of ITT Industries, Inc. is under contract to assist NASA GRC in the technology pre-screening task. They and other contractors of NASA and the FAA will have access to the information submitted for the purpose of conducting the technology pre-screening process.

NASA GRC seeks information on candidate system solutions for mobile communications that can be used for ATS both domestically and internationally. Both current capabilities (based on existing or planned products) and potential future concepts are encouraged in response to this RFI. Concepts based on terrestrial broadcast, air-to-air relay, and/or satellite relay are acceptable as inputs to the technology pre-screening process.

It is desirable that information provided to describe the advanced air-ground communications system concepts include:

- A technical description of the system solution including but limited to: air interface; end-to-end latency (pilot-to-controller and controller-to-pilot if asymmetric); ATS communications services provided; protocols; network topology; spectrum required; security features; and any simplifying assumptions needed to meet or exceed the design goals described below.
- Areas of expected improvement over current air-ground communications systems for ATS.
- Scalability of the system to meet increasing demands and the system's ultimate total capacity.
- A description of the impact (high-level transition plan, schedule and relative cost) on current airborne and ground avionics and infrastructure.
- Technical maturity of the system solution, including status of applicable standards, commercial availability of electronics, and estimates of time for infusion into the National Airspace System.

The following high-level functional design goals for a mobile air-ground communications system to be used in providing ATS are intended to provide insight into the performance of the current system, and desired characteristics of a future system:

- Increase the channel capacity of the current air-ground communications system.
- Utilize the VHF aeronautical communications frequency band, or justify the utilization of other aeronautical frequency allocations.
- Provide for an orderly and efficient transition from the current VHF communications system.
- Provide a mechanism for "real-time" voice, with requisite combined performance in latency and channel access that promotes efficient and effective communications between a controller and the set of aircraft within the controlled airspace.
- Provide a mechanism for both addressable and broadcast data functions.
- Provide a mechanism to specify various Quality of Service (QoS) classes for data transfer.
- Within each QoS class, provide a mechanism for scheduling and prioritizing data delivery.
- Include configurable security measures to provide user authentication features.
- Provide a mechanism to control multiple sectors in the same geographic area.

- Provide aircraft position location capability.

Description of Responses:

NASA received 24 RFI responses. The responses have been color coded and tabulated as shown below and include details as to whether a particular technology offered a solution and if yes, what the solution was and whether the solution is relevant to the problem at hand. The response also includes information regarding copyrights for the considered technology, whether it is proprietary or for limited use only.

Table 2

Respondent	Solution	Comments	Discussed in...
AgileAccess™ Technologies	N/A	No solution provided in RFI. Overview of company capabilities for circuit and PCB design as well as failure analysis.	N/A
Agilent and Thales	WCDMA or CDMA2000	Technologies are already being considered.	2G/3G Cellular Derivatives
AirNav, Inc (Bob Crow)	Integrated Global Surveillance and Guidance System	RFI describes a full duplex and simplex channelization of the 960 to 1030 MHz band. Digital voice and data services on an 8-PSK 25 kHz channelization system. Insufficient information provided to Evaluate.	N/A
Alcatel	SDLS	Technology is already being considered.	SATCOM
Analytical Graphics	N/A	No solution provided in RFI. Overview of COTS software products: STK and Navigation Toolkits.	N/A
ARINC and ViaSat	Link16	Technology is already being considered.	Military
Avionics Engineering Center Ohio University	N/A	No solution provided in RFI. Mentions that CDMA might be a promising technology.	N/A
B-12	Packet Radio	Doesn't Meet Latency Requirements.	N/A
Boeing	Next Generation FANS over Aero-BGAN network	RFI describes the provisioning of party-line voice and enhanced ADS-B (enhanced over regular FANS) over Inmarsat satellite constellations. Paper provides a detailing of operational benefits (including an analysis framework for deriving operational requirements), avionics architecture and a transition plan.	SATCOM
Cisco Systems	N/A	No solution provided in RFI.	N/A
Frequentis	B-VHF	Technology is already being considered.	Custom Broadband
	Safety and Security Enhanced Voice	No increase in Voice Capacity	N/A
General Dynamics	Satellite Netted Radio (SNR) and Data Under Voice (DUV)	RFI describes using the Iridium system (although the concept can be extended to other satellite services) to provide ATC voice, ADS-B, TIS and FIS data. SNR and DUV are described as techniques that can make the provisioning of satellite services for ATC	SATCOM
Harris	VDL-3	Technology is already being considered.	Custom Narrowband (VHF)
	VoIP on OFDM in MLS Band	Technology is similar to IEEE 802 technology.	IEEE 802 Derivatives
Israel Aircraft Industries, Ltd. (IAI), MLM Division	Air Traffic Data Link (ATDL)	RFI describes a system that would require an R&D effort to transform a military training system to a commercial product. As stated, the intent of the system is to form ad-hoc networks for the dissemination of position and A/C status information	N/A
ITT Industries—ACD and TrellisWare Technologies	VDL-3 plus Single Antenna Interference Cancellation	Technology is a modification to VDL-3 system to provide increased spectrum efficiency.	Custom Narrowband (VHF)
NASA Ames Research Center	N/A	No solution provided in RFI. Provided two papers that discuss the impact of voice, data link, and mixed air traffic control environments on flight deck procedures.	N/A
OAG	N/A	No solution provided in RFI. Response describes the OAG airline schedule database and provides a description of the database field structure and some sample data.	N/A
Raytheon	N/A	No solution provided in RFI. Provided in depth analysis of suitability of TDMA, CDMA, LEO, GEO, Packet Radio	N/A

		and VoIP.	
Redflex Communications	N/A	No solution provided in RFI.	N/A
Rockwell Collins	VDL-E		Custom Narrowband VHF
Sensis and Seagull Technology, Inc.	Flash OFDM	Proprietary (Flarion)	N/A
	B-VHF	Technology is already being considered.	Custom Broadband
	Smart Antennas	Not a complete solution, but rather an enabling technology.	N/A
SITA	VDL-2	Technology is already being considered.	Custom Narrowband (VHF)
	IP over VDL-2	Technology is similar to VDL-2.	Custom Narrowband (VHF)
	Classic Inmarsat SATCOM	Technology is already being considered.	SATCOM
	Swift 64	Technology is already being considered.	SATCOM
	Aero-BGAN	Technology is already being considered.	SATCOM
SOFREAVIA	E-TDMA	RFI describes E-TDMA, a Statistical Self-Synchronizing system that utilizes a cellular layout (layout is periodically broadcast on GSC and also loaded pre-flight) and aircraft initiated handovers. System is intended for ADS-B with QoS provisioning at the	Custom Narrowband (VHF)
University Research Foundation Maryland Advanced Development Laboratory Division	Advanced Slotted Ring	Technology is a ground based network communications technology with no defined air interface.	N/A

Color Legend:

- RFI response provided a new technology solution that is discussed in '_____',
- RFI response provided a duplicate technology solution that is discussed in '_____',
- RFI response provided a technology solution, but Minimum Threshold Requirements not met
- RFI response did not provide a technology solution

Appendix D—Technology Characterization Form

Each evaluated technology was characterized in accord with the following form.

<Technology>		
Author:	Last Updated:	
ITEMS	DESCRIPTION	
AIR INTERFACE STANDARDS AND TECHNOLOGY EMPLOYED		
Duplexing scheme	<input type="checkbox"/> Duplex (FDD) <input type="checkbox"/> Duplex (TDD) <input type="checkbox"/> Simplex <input type="checkbox"/> Semi-Duplex	
Multiple-Access scheme	<input type="checkbox"/> TDMA <input type="checkbox"/> FDMA <input type="checkbox"/> CDMA <input type="checkbox"/> CSMA	
Modulation types		
Vehicle Speed Supported		
Maximum Range Supported		
FEC Coding		
Diversity techniques		
Signal bandwidth		
Supported data rates per user		
Max. number of simultaneously supported users per sector/cell		
Design Frequency Band		
Proposed Frequency Band	<input type="checkbox"/> VHF (118 to 138 MHz) <input type="checkbox"/> Non-VHF (__)	
Current spectrum status		
Propagation		
Available spectrum bandwidth		
Remarks		
COMMUNICATION SERVICES PROVIDED		
Service Type 1	Voice: Pilot-Controller Party Line	
Is service provided?	<input type="checkbox"/> Native <input type="checkbox"/> Work around <input type="checkbox"/> Appliqué	
Vocoder		
Voice Latency		
Time to Connect		
PTT Implementation	<input type="checkbox"/> Native <input type="checkbox"/> Work around <input type="checkbox"/> Appliqué	

Service Type 2	Voice: Pilot-Controller Selective Addressing	
Is service provided?	<input type="checkbox"/> Native <input type="checkbox"/> Work around <input type="checkbox"/> Appliqué	
Vocoder		
Voice Latency		
Time to Connect		
Service Type 3	Voice: Pilot-Pilot	
Is service provided?	<input type="checkbox"/> Native <input type="checkbox"/> Work around <input type="checkbox"/> Appliqué	
Vocoder		
Voice Latency		
Time to Connect		
PTT Implementation	<input type="checkbox"/> Native <input type="checkbox"/> Work around <input type="checkbox"/> Appliqué	
Service Type 4	Data: Air-Ground	
Is service provided?	<input type="checkbox"/> Native <input type="checkbox"/> Work around <input type="checkbox"/> Appliqué	
User throughput		
Prioritization	<input type="checkbox"/> Yes <input type="checkbox"/> No	
Data Services Provided	<input type="checkbox"/> Circuit <input type="checkbox"/> Packet <input type="checkbox"/> Addressed <input type="checkbox"/> Packet <input type="checkbox"/> Broadcast	
Service Type 5	Data: Air-Air (no intermediary)	
Is service provided?	<input type="checkbox"/> Native <input type="checkbox"/> Work around <input type="checkbox"/> Appliqué	
User throughput		
Prioritization	<input type="checkbox"/> Yes <input type="checkbox"/> No	
Data Services Provided	<input type="checkbox"/> Circuit <input type="checkbox"/> Packet <input type="checkbox"/> Addressed <input type="checkbox"/> Packet <input type="checkbox"/> Broadcast	
Service provision possible model		
Remarks		
CHANGES TO AND IMPACTS ON REFERENCE ARCHITECTURE		
Avionics	<input type="checkbox"/> New Radio <input type="checkbox"/> New Antenna <input type="checkbox"/> Antenna Duplexer	

	<input type="checkbox"/> Timing Source <input type="checkbox"/> Additional Equipment	
Mutual spectrum compatibility		
Ground infrastructure evolution	<input type="checkbox"/> New Radio <input type="checkbox"/> New Antenna <input type="checkbox"/> Antenna Duplexer <input type="checkbox"/> Timing Source <input type="checkbox"/> Additional Equipment	
Geographical coverage	<input type="checkbox"/> Global (including polar) <input type="checkbox"/> Non-polar <input type="checkbox"/> Continental <input type="checkbox"/> Local	
Type of system	<input type="checkbox"/> Terrestrial <input type="checkbox"/> Satellite <input type="checkbox"/> Air-to-Air <input type="checkbox"/> Hybrid	<u>If Hybrid, explain:</u>
Number and type of satellites		
Remote site density	<input type="checkbox"/> More dense <input type="checkbox"/> Comparable <input type="checkbox"/> Less dense	
Telco Bandwidth Required		
Remarks		
STANDARDIZATION AND INDUSTRIAL MATURITY		
Status of development of the necessary components by the industry		
Standardization status		
Remarks		
OTHER		
Migration/Transition identified issues		
Allow incremental deployment		
Inband transition		
Security function supported		
Interference Resilience		
Remarks		
High level description		

Appendix E—List of Acronyms and Abbreviations

The following list identifies acronyms and abbreviations used throughout this report.

1G	1st generation cellular
1x	Single Carrier
2G	2nd generation cellular
3G	3rd generation cellular
3GPP	Third Generation Partnership Project
3GPP2	Third Generation Partnership Project 2
3x	Multi-Carrier
4G	4th generation cellular
AAC	Airline Administrative Communications
ACARS	Airborne Communications and Reporting System
ACELP	Algebraic Code Excited Linear Prediction
ACP	Aeronautical Communications Panel
ADL	Airport Data Link
ADS-B	Automatic Dependent Surveillance Broadcast
AEEC	Airlines Electronic Engineering Committee
Aero-BGAN	Aeronautical Broadband Global Area Network
AES	Airborne Earth Station
AI	Air Interface
AJ	Anti-jam
AM(R)S	Aeronautical Mobile (Route) Service
AMR	Adaptive Multi-Rate (type of codec)
AMSC	American Mobile Satellite Corporation
AMSS	Aeronautical Mobile Satellite Services
ANG	Air National Guard
ANSI	American National Standards Institute (www.ansi.org)
AOC	Air Operations Center
AOC	Airline Operational Control
AP	Access Point
APC	Airline Passenger Communications
APCO	Association of Public-Safety Communications Officers
APIM	ARINC IA Project Initiation/Modification
ARINC	Aeronautical Radio, Inc.
A-SMGCS	Advanced Surface Movement and Guidance System
ATCRBS	Air Traffic Control Radio Beacon System
ATM	Air Traffic Management
ATN	Aeronautical Telecommunications Network
ATS	Air Traffic Services
AUC	Authentication Center
AVLC	Aviation VHF Link Control
BA	Base Audio
BC	Base Control
BE	Best Effort Service
BER	Bit Error Rate
BGAN	Broadband Global Area Network
BLOS	Beyond LoS
BOC	Billing Operations Center

BPSK	Binary Phase Shift Keying
BR	Base Radio
BSC	Base Station Controller
BSS	Base Station Subsystem
BTS	Base Transceiver Station
B-VHF	Broadband VHF
C/N	Carrier/Noise power ratio measured in dB
C4FM	Constant Envelope 4-Level Frequency Modulation
CAA	Civil Aviation Authority
CANTCO	Can't Comply
CBB	Connexion By Boeing
CCI	Co-channel Interference
CCK	Complementary Code Keying (RF modulation)
CDMA	Code Division Multiple Access
CLI	Calling Line Identification
CLNS	Connectionless Network Service
CM	Configuration Management
CMU	Communications Management Unit
CNS	Communication, Navigation, Surveillance
CODEC	Combined Coder and Decoder
COFDM	Coded Orthogonal Frequency Division Multiplexing
CON	Console
CONS	Connection Oriented Network Service
CPDLC	Controller Pilot Data Link Communications
CQPSK	Compatible Differential Offset Quadrature Phase Shift Keying
CRC	Cyclic Redundancy Code
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
D8PSK	Differential 8-ary Phase Shift Keying
DCN	Data Core Network
DECT	Digital Enhanced (formerly “European”) Cordless Telecommunications
DHCP	Dynamic Host Control Protocol
DLE	Data Link Entity
DLS	Data Link Services
DME	Distance Measuring Equipment
DMO	Direct Mode Operation
DQPSK	Differential Quaternary Phase Shift Keying
DSB-AM	Double Sideband Amplitude Modulation
DSSS	Direct Sequence Spread Spectrum
DULGARS	Dual Channel Ground and Airborne Radio System
DVSI	Digital Video Systems, Inc.
EDACS	Enhanced Digital Access Communications System
EDGE	Enhanced Data Rates for GSM Evolution
EIR	Equipment Identity Register
EMS	European Mobile Services
EPLRS	Enhanced Position Location Reporting System
ERF	Electronic Remote Fill
ESA	European Space Agency
E-TDMA	Enhanced Time Division Multiple Access

ETSI	European Telecommunications Standards Institute
EU	European Union
EV	Evolution
EV-DO	Evolution Data Only
EV-DV	Evolution Data and Voice
EVRC	Enhanced Variable-Rate Codec
FAA	Federal Aviation Administration
FAC	Forward Auxiliary Carrier
FANS	Future Air Navigation System
FCC	Federal Communications Commission
FCC	Forward Common Carrier
FCOCR	Final Communication Operating Concept and Requirements
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FED	Federal Government
FH	Frequency Hopping
FHSS	Frequency Hopping Spread Spectrum
FIS-B	Flight Information Service
Flash OFDM	Flash Orthogonal Frequency Division Multiplexing
FLIPCY	Flight Plan Consistency
FRC	Forward Reference Carrier
GACS	Global Aeronautical Communications System
GCNSS	Global Communication Navigation and Surveillance System
GEO	Geostationary or Geosynchronous Earth Orbit
GES	Ground Earth Station
GFSK	Gaussian Frequency Shift Keying
GGSN	Gateway GPRS Support Node
GPRS	General Packet Radio Services
GSM	Global System for Mobile Communications
GSM-R	Global System for Mobile Communications Rail Extension
GTP	GPRS Tunneling Protocol
HAVCO	Have complied
HDLC	High Level Data Link Control
HFDL	High Frequency Data Link
HLR	Home Location Register
HR-DSSS	Hi Rate—Direct Sequence Spread Spectrum
IBSS	Independent BSS
ICAO	International Civil Aviation Organization
ICNIA	Integrated Communications Navigation and Identification Avionics
ICOCR	Initial Communication Operating Concept and Requirements
iDEN	Integrated Dispatch Enhanced Network
IDRP	Inter-Domain Routing Protocol
IEC	International Electro-technical Commission
IEEE	Institute of Electrical and Electronics Engineering
IETF	Internet Engineering Task Force
IFF	Identification Friend or Foe
IGSAGS	Integrated Global Surveillance and Guidance System
IMBE	Improved Multi-Band Excitation
IOTA	Isotropic Orthogonal Transform Algorithm

IP	Internet Protocol
IPsec	IP Security
IPT	Integrated Product Team
IPv4	IP version 4
IPv6	IP version 6
IRL	Implementation Readiness Level
ISDN	Integrated Services Digital Network
ISO	International Standards Organization
ITU	International Telecommunications Union
ITU-T	International Telecommunications Union-Telecommunications Sector
JRE	Joint Range Extension
JREAP	JRE Application Protocol
JTIDS	Joint Tactical Information Distribution System
JTRS	Joint Tactical Radio System
LAN	Local Area Network
LEO	Low Earth Orbit
LME	Link Management Entity
LoS	Line of Sight
LPI	Limited Probability of Intercept
LVT	Low Volume Terminals
MAC	Media Access Control
MAN	Metropolitan Area Network
MASPS	Minimum Aviation System Performance Standards
MC-CDMA	Multi-Carrier Code Division Multiple Access
MC-TDMA	Multi-Carrier Time Division Multiple Access
MDP	Mobile Data Peripheral
MDR	Multi-Mode Digital Radio
MEO	Middle Earth Orbit
MESA	Mobility for Emergency and Safety Applications
MHz	Megahertz
MIDS	Multifunctional Information Distribution System
MLS	Microwave Landing System
MOPS	Minimum Operational Performance Standards
MPDS	Mobile Packet Data Service
MRC	Mobile Radio
MRC	Mobile Router and Control
MSBN	Mobile Satellite Business Network
MSC	Mobile Switching Center
MSK	Minimum Shift Keying
MTSAT	Multifunctional Transport Satellite
NAS	National Airspace System
NASTD	National Association of State Telecommunications Directors
NATO	North Atlantic Treaty Organization
NCS	Network Control Station
NMS	Network Management System
NMS	Network Master Station
NOC	Network Operations Center
NPG	Network Participation Group
nrtPS	Non-Real-Time Polling Service
NSS	Network Subsystem

OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open Systems Interconnection
OTAR	Over The Air Re-keying
OTH	Over the Horizon
P2DP	Packed-2 Double Pulse
P2P	Peer-to-peer
P2SP	Packed-2 Single Pulse
P4SP	Packed-4 Single Pulse
PAMR	Public Access Mobile Radio
PAN	Personal Area Network
PCM	Pulse Code Modulation
PCN	Personal Communications Network
PCU	Packet Control Unit
PD	Packet (Mode) Data
PEI	Peripheral Equipment Interface
PMR	Private Mobile Radio
PoC	PTT Over Cellular
PPDR	Public Protection and Disaster Relief
PPP	Point to Point Protocol
PSPP	Public Safety Partnership Project
PSTN	Public Switched Telephone Network
PSWAC	Public Safety Wireless Advisory Committee
PTM	Point-to-Multipoint
PTP	Point-to-point
PTT	Push-To-Talk
QAM	Quadrature Amplitude Modulation
QCELP	Qualcomm's Code Excited Linear Prediction
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RAC	Return Auxiliary Carrier
RCE	Radio Control Equipment
RFC	Radio Frequency Control
RFG	Radio Frequency Gateway
RFI	Request For Information
RFS	Radio Frequency Switch
RIU	Radio Interface Unit
RPDE	Rapid Preliminary Development Effort
RRC	Return Reference Carrier
RTCA	Radio Technical Commission For Aeronautics
RTP	Real-Time Transit Protocol
rtPS	Real-Time Polling Service
RTT	Radio Transmission Technology
RUDICS	Routed Unstructured Digital Interworking Connectivity Service
SA	Situation Awareness
SADL	Situation Awareness Data Link
SAIC	Single Antenna Interference Cancellation
SAM	Scalable Adaptive Modulation
SAP	Service Access Point
SARPS	Standards and Recommended Practices
SAS	Satellite Access Station

SATCOM	Satellite Communications
SC	Single Channel
SCADA	Supervisory Control and Data Acquisition
SCC	Satellite Control Center
SCDMA	See CDMA
SDLS	Satellite Data Link System
SDS	Short Data Service
SGSN	Serving GPRS Support Node
SIM	Subscriber Identity Module
SINGARS	Single Channel Ground and Airborne Radio System
SITA	Société Internationale Télécommuniqué Aéronautique
SMS	Short Messaging Service
SnAP	Subnetwork Access Protocol
SNMP	Simple Network Management Protocol
SOR	Statement of Requirements
STDP	Standard Double Pulse
TACP	Tactical Air Control Party
TARMAC	Taxi and Ramp Management and Control
TCP	Transmission Control Protocol
TCP/IP	Terminal Control Protocol/Internet Protocol
TDD	Time Division Duplex
TDL	Tactical Data Link
TDMA	Time Division Multiple Access
TD-SCDMA	Time Duplex-Synchronous Code Division Multiple Access
TEDS	TETRA Enhanced Data Service
TELCO	Telephone Company
TETRA	TERrestrial TRunked RADio
TETRA MoU	TERrestrial TRunked RADio Memorandum Of Understanding
TIA	Telecommunications Industry Association
TOC	Tactical Operations Center
TRL	Technology Readiness Level
TSR	Time Slot Reallocation
UAT	Universal Access Transceiver
UDP	User Datagram Protocol
UGS	Unsolicited Grant Service
UHF	Ultra High Frequency
UMTS	Universal Mobile Telecommunications Service/ 3G technology
UNNI	Unlicensed National Information Infrastructure
USSD	Unstructured Supplementary Service Data
UTRA	UMTS Terrestrial Radio Air Interface
V+D	Voice plus Data
VDL	Very High Frequency Digital Link
VHF	Very High Frequency
VLR	Visitor Location Register
VME	VDL Management Entity
VMF	Variable Message Format
VoIP	Voice over Internet Protocol
VSAT	Very Small Aperture Terminal
VSELP	Vector Sum Excited Linear Predictors
VSS	VDL Mode 4 Specific Services

WAN	Wide Area Network
WAP	Wireless Application Protocol
W-CDMA	Wideband Code Division Multiple Access
Wi-Fi	Wireless Fidelity
WILCO	Will Comply
WiMAX	Worldwide Interoperability Microwave Access
WRC	World Radiocommunications Conference

Appendix F—End Notes

¹ Working Paper (WP)/02

² ICAO Global Plan

³ Eurocontrol, “UMTS/FDD OPERATING AT C-BAND:PHYSICAL LAYER VALIDATION REPORT,” (October 2003).

⁴ ICAO ACP WGC7/WP15

⁵ ICAO ACP WGC7/WP15

⁶ Trunking refers to the provisioning of multiple frequencies for one common radio network. There is typically a trunking control channel, which is used to control network access. When a user keys his radio, messages are sent on the trunking control channel to the trunking controller. The trunking controller assigns an available channel, and messages all of the member of the talk group, initiating radio tuning to the designated channel, and then enabling communications on that channel. Trunked radio systems allow more users to be accommodated than a conventional radio system for a given probability of blocking. Consequently, they are deemed to be more spectrally efficient than conventional radio systems by the NTIA.

⁷ According to Robert I. Desourdis, Jr., et al., in their book “emerging public safety wireless communication systems”, Artech House, 2002: “The first enhanced specialized mobile radio (ESMR) network was launched in 1993 by Nextel, which added a cellular capability and is now the world’s largest ESMR. Nextel uses Motorola’s Integrated Dispatch Enhanced Network (iDEN) technology. The iDEN channel access technique is based on TDMA, with six time slots for two-way dispatch and three time slots for cellular interconnection. Modulation is a proprietary scheme known as M16 quadrature amplitude modulation (QAM), which packs 64 Kbps into a 25-kHz bandwidth.” There exists some evidence that Nextel is considering an upgrade to WiDEN, a more capable, but also proprietary, Motorola technology. Information about WiDEN is sketchy. Wikipedia (<http://en.wikipedia.org/wiki/iDEN>) has the following description for WiDEN in its iDEN entry: “Nextel, in order to provide high data rates for Packet Data, is providing a mid next generation technology called WiDEN. WiDEN is an expansion on the current iDEN system, where instead of using a normal 25kHz channel for packet data, it will encompass 4 carriers (100 kHz) into one channel.” The sketchy information that is available about WiDEN would seem to indicate that it is likely comparable to P34 (256 kbps WiDEN data rate for a 100 kHz channel, as opposed to between 153 and 460 using P34 on the same 100 kHz channel). Concerns about the proprietary nature of the technology and its propagation range due to its TDMA access scheme would weigh against the advantages that it might provide with its two-way dispatch capabilities. The technology was not evaluated.

⁸ Association of Public Safety Communications Officials (APCO), *The Application of the 900 MHz Band to Law Enforcement Communications—An Analysis of Technical and Regulatory Factors Affecting the Applicability of the 900 MHz Portion of the Radio Spectrum to Law Enforcement Communication System Problems*, February 1978

⁹ Association of Public Safety Communications Officials (APCO), *The Operational Impact of 900 MHz Radio Systems on Law Enforcement Communications—An On-Site Review of Current Systems in Miami, FL, Orange County, CA, and Chicago, IL*, December 1978

¹⁰ Association of Public Safety Communications Officials (APCO), *900 MHz Trunked Communications System Functional Requirement Development—The Identification of the Specific Operational Capabilities That Should Be Incorporated in a Demonstration Trunked Communication System for Law Enforcement Agencies*, March 1979.

¹¹ Compendium of Emergency Communications and Communications Network Security-related Work Activities within the Telecommunications Industry Association (TIA), TIA, 2003

¹² *ibid.*, p. 9

¹³ TETRA Release 2, Dr. M. Nouri, New Technologies Senior Manager, Marconi Mobile, October 2002 presentation to ETSI

¹⁴ It is instructive to look at *the Final Report of the Public Safety Wireless Advisory Committee* to glean generic public safety communication requirements. Voice services are identified as a critical element of communications, with requirements for central control of mobile units, all-informed groups (termed open-channel operation in the public safety domain and party-line in the aeronautical communications domain), one-to-many communications and one-to-one communications as required functional elements of the system. These functional requirements align very nicely with the functional requirements identified as the voice pre-screening criteria (see Section 2 of this report). Additionally, a push for spectral efficiency and interoperability are also common themes between the Public Safety Radio technologies and the requirements of the future aeronautical communications system.

¹⁵ FAA’s Office of System Architecture and Investment Analysis, National Airspace System Engineering Manual, Version 1.0, November 1, 2002, p. 4.6-11.

¹⁶ Report ITU-R M.2014, Spectrum Efficient Digital Land Mobile Systems for Dispatch Traffic, 1998, p. 5.

¹⁷ *ibid.*

¹⁸ *ibid.*

¹⁹ *ibid.*

²⁰ *ibid.*

²¹ TIA Document, TIA-902.BBAB, Wideband Air Interface Isotropic Orthogonal Transform Algorithm (IOTA) Physical Layer Specification Public Safety Wideband Data Standards Project—Digital Radio Technical Standards, March 2003, p. 20.

²² TIA Standard, ANSI/TIA-902.BAAB-A, Wideband Air Interface Scalable Adaptive Modulation (SAM) Physical Layer Specification—Public Safety Wideband Data Standards Project—Digital Radio Technical Standards, September 23, 2003, p. 28.

²³ TETRA Release 2, Dr. M. Nouri, New Technologies Senior Manager, Marconi Mobile, October 2002 presentation to ETSI, Slide 18.

²⁴ *ibid.*, Slide 21.

²⁵ A related, and equally important justification concerning technical maturity needs to be made here. The aviation industry has already standardized a narrowband TDMA system that is optimized for the propagation considerations of the Air-Ground channel. This system is VDL Mode 3. VDL Mode 3 maturity is such to render moot any recommendation of a narrowband Public Safety TDMA system, with an air interface that requires modifications to meet the required communications distances of aeronautical communications. In essence, these technologies were not selected for analysis in deference to VDL Mode 3, which was acknowledged to be a more capable and technically mature technology that could have been classified in the Public Safety-Narrowband-TDMA bin.

²⁶ TIA/EIA TELECOMMUNICATIONS SYSTEMS BULLETIN, APCO Project 25 System and Standards Definition, TSB102-A, (Revision of TSB102), NOVEMBER 1995, pp. 54-55.

²⁷ TIA/EIA TELECOMMUNICATIONS SYSTEMS BULLETIN, APCO Project 25 System and Standards Definition, TSB102-A, (Revision of TSB102), NOVEMBER 1995, p. 32

²⁸ *ibid.*

²⁹ *ibid.*, p. 33.

³⁰ *ibid.*, pp. 33-38.

³¹ TIA TSB-102.AABD p. 14

³² Project 25/34 Statement of Requirements, Revision 4.00 June 1, 1999

³³ HIGH-LEVEL FEASIBILITY STUDY OF UMTS FOR AIR TRAFFIC CONTROL, Jaquet-Droz, Eurocontrol document dated 31 August 2000, p. 62

³⁴ *ibid.*, p. 60

³⁵ Analysis and Optimization of the Performance of OFDM on Frequency-Selective Time-Selective Fading Channels, Heidi Steendam and Marc Moeneclaey, IEEE TRANSACTIONS ON COMMUNICATIONS, VOL. 47, NO. 12, DECEMBER 1999, p. 1817

³⁶ The authors make no claim of equivalence between the Public Safety Service requirements and the Aeronautical Safety Service requirements, nor can we provide a supporting analysis that would equate them. This technology was graded a yellow in accord with the consensus evaluation criteria and associated metrics. Both the FAA and Eurocontrol have reviewed the evaluation criteria; the metrics for evaluation were *developed* by the FAA transition analysis team. Clearly, as this study progresses, if a Public Safety technology is recommended for use in a future air-ground communications system, safety analysis in accord with the standard aviation methodologies will be conducted. The goodness of this assumption will be verified in time.

³⁷ *Ab antecedo*

³⁸ The P34 air interface provides two forms of scalability. Adaptive modulation is accommodated, which means that the offered data rate scales by varying the signal constellation complexity (from QPSK to 16QAM to 64QAM) as the channel conditions warrant. While this is an extremely useful feature, it is not the primary advantage of the technology, as many modern communications systems employ adaptive modulation. Both the Scaleable Adaptive Modulation (SAM) and Isotropic Orthogonal Transform Algorithm (IOTA) physical layers of P34 were designed to accommodate incremental addition of capacity by scaling the physical layer parameters. To be less abstract, imagine a P34 system that is initially deployed with a 50 kHz channelization (on one of the allocated channels in the 700 MHz band for Public Safety communications, or even on a future 50 kHz channel that has been defined in the DME band for ATC communications). Should the service provider note (from say, his automated collection of network statistics) that this particular sector has been experiencing system congestion, the standard provides for a doubling of system capacity by what is for all intents and purposes the same physical waveform, with an addition of an extra complement of carriers (eight for SAM, which increases the bandwidth from 50 kHz to 100 kHz) and a repetition of the time domain frame. Presumably the frequency of operation would be changed to a frequency that has been allocated for 100 kHz, which would clearly require frequency planning and coordination activities, but the radio equipment and associated infrastructure would remain unchanged.

³⁹ Comparison of Broadband Aeronautical Satellite Communications Systems: L-Band versus Ku-Band, Michael de La Chapelle, et al, 9th Ka and Broadband Communication Conference, Nov. 5-7, 2003, p. 5

⁴⁰ Pat de Barros, Senior Program Manager, GLOBALink/HF Data Link, HF Data Link Background and Future Plans, ICNS Conference, May21, 2003, Slide 3.

⁴¹ *ibid.*

⁴² ACP WGC8/WP3, AERONAUTICAL COMMUNICATIONS PANEL (ACP), Working Group C—7th meeting, Munich, Germany, 20-24 September 2004, Report of the Technology assessment Group, p. 11.

⁴³ *ibid.*

⁴⁴ Satellite S Band Radio Frequency Table, <http://www.csgnetwork.com/satradiofreq.html>

⁴⁵ Robert P. Crow, AirNav, Inc., Civil Aviation's Next Generation Global CNS/ATM System, p. 35.

⁴⁶ *ibid.* Note that at least two interpretations can be made from the quoted page. In the first, a D8PSK signal is transmitted at 10,000 symbols per second. The second interpretation is a 10,000 bit per second data rate with a three bit spreading code. Neither interpretation changes the evaluation of the system.

⁴⁷ SDLS-ASP-SP-0031, SDLS Slice 3—Executive Summary, Alcatel Space, February 20, 2004, p. 13.

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- ⁴⁸ ACP WGC8/WP3, AERONAUTICAL COMMUNICATIONS PANEL (ACP), Working Group C—7th meeting, Munich, Germany, 20-24 September 2004, Report of the Technology assessment Group, p. 9. Note that in the Executive Summary document (cited above) the specified data rate for low gain antennas is 5.5 kbps.
- ⁴⁹ Thuraya web page, <http://www.thuraya.com/tech/>
- ⁵⁰ *ibid.*
- ⁵¹ ACP WGC8/WP3, AERONAUTICAL COMMUNICATIONS PANEL (ACP), Working Group C—7th meeting, Munich, Germany, 20-24 September 2004, Report of the Technology assessment Group, p. 13.
- ⁵² *ibid.*
- ⁵³ MIT Industry Systems Study, Communications Satellite Constellations, Technical Success and Economic Failure, Version 1.1, October 14, 2003, p. 21.
- ⁵⁴ Small Satellites Home Page, http://centaur.sstl.co.uk/SSHP/data/data_globalstar.html
- ⁵⁵ See for instance, MIT Industry Systems Study, Communications Satellite Constellations, Technical Success and Economic Failure, Version 1.1, October 14, 2003, p. 18. It is interesting to note that Iridium is not actually allocated the entire spectrum specified in table 3.5-2 in every region of the world. In fact, this reference indicates that in the United States, the Iridium allocation is only 1621.35-1626.5 MHz.
- ⁵⁶ *ibid.*
- ⁵⁷ The authors do not discount the importance of the HF Data Link as a current and operational system. We expect this system to be operational for the foreseeable future, and to be an important component of A/G communications, providing data services in remote regions. The “No” in the “Evaluate” column simply indicates that the system is clearly not a solution for congestion in the VHF Band, which is a primary driver for this study. It does not and can not provide additional voice channels.
- ⁵⁸ David C. Morse, et. al., Next Generation FANS over INMARSAT Broadband Global Area Network (BGAN), Draft paper to be submitted to DASC 2004, p. 3
- ⁵⁹ Aero-BGAN Broadband Global Area Network, Presentation by Gary Colledge Manager Aeronautical Data and Safety Services at Eurocontrol NexSat Steering Group 5—Brussels Nov 2004, Slide 13.
- ⁶⁰ JM Gaubert, SDLS Slice 3 Executive Summary, SDLS-ASP-SP-0031 Issue 3, February 20, 2004, p. 17
- ⁶¹ *ibid.*, p. 19
- ⁶² SDLS (Satellite Data Link System) System Presentation, ICAO ACP Working Group C, Toulouse, October 2003, ACP WGC6/WP19, Slide 21.
- ⁶³ *ibid.*, p. 12
- ⁶⁴ SDLS Demonstrator Final Report, SDLS-APSI-TN-0132, August 30, 2002, p. 14
- ⁶⁵ Daniel Schwartz, Director Transportation Market, Iridium Satellite, LLC, Iridium System and Services Overview, PowerPoint Presentation, July 2004, Slide 6.
- ⁶⁶ *ibid.*, Slide 3. Note that a vertical market is a particular industry or group of enterprises in which similar products or services are developed and marketed using similar methods. This can be contrasted with a horizontal market, a term used to indicate a cross-section of industries. The original Iridium marketing strategy had been to pursue a broad cross-section of cellular users. The new focus is on vertical market segments, such as aeronautical, military, and maritime market segments.
- ⁶⁷ *ibid.*, Slides 35-36.
- ⁶⁸ *ibid.*, Slide 37.
- ⁶⁹ This discussion assumes that the entire 10.5 MHz of spectrum is available for use. Regional restrictions (as does the frequency reuse pattern between beams) can reduce the number of available channels substantially. In the United States, Iridium is licensed for operation in a portion of the frequency band 1610 to 1626.5 MHz.
- ⁷⁰ NAS-SR-1000, March 21, 1985, Paragraph 3.8.1.B
- ⁷¹ Basu, S. and MacKenzie, E., “Ionospheric Constraints on VHF/UHF Communications Links during Solar Maximum and Minimum Periods”, *Radio Science*, Vol. 23, No. 3, 1988, pp. 363-378
- ⁷² Global Communication, Navigation & Surveillance System (GCNSS) System Architecture Description Document (SADD); Volume III—Space-Based Communication Navigation & Surveillance (CNS) Enhancement; Boeing Document Number D794-10025-1 Vol. III, Section six.
- ⁷³ Global Communication Navigation & Surveillance System (GCNSS), Phase I, Concept Exploration and Demonstration, Program Summary, Boeing Document Number D794-10147-1, pp. 9-10
- ⁷⁴ *ibid.*, p. 10.
- ⁷⁵ APIM—Inmarsat BGAN SATCOM for Broadband and ATC Communications, ARINC IA Project Initiation/Modification (APIM), APIM #: 04-001, p. 1
- ⁷⁶ NEXCOM Very High Frequency Digital Link Mode 3 (VDL3) Latency Study Briefing for RTCA, July 9, 2002, Randy L. Sollenberger, Ph.D., Engineering Research Psychologist, ACB-220, Un-numbered RTCA SC-172 WP
- ⁷⁷ ITU-T P.11, Telephone Transmission Quality, Vocabulary and Effects of Transmission Parameters on Customer Opinion of Transmission Quality and Their Assessment, Effect of Transmission Impairments, p. 8
- ⁷⁸ ITU Transmission Systems and Media, General Recommendations on the Transmission Quality for an Entire International Telephone Connection (ITU-T G.114)
- ⁷⁹ Global Communication Navigation & Surveillance System (GCNSS), Phase I, Concept Exploration and Demonstration, Program Summary, Boeing Document Number D794-10147-1, pp. 11

⁸⁰ David C. Morse, et. al., Next Generation FANS over INMARSAT Broadband Global Area Network (BGAN), Draft paper to be submitted to DASC 2004, p. 3

⁸¹ The number of calls per beam was derived by taking the Boeing numbers, “240 kbps average throughput per channel with a maximum of ~16 channels per beam”, and scaling by a factor of 10kbps per voice call (24*16=384).

⁸² SDLS (Satellite Data Link System) System Presentation, ICAO ACP Working Group C, Toulouse, October 2003, ACP WGC6/WP19, Slide 13.

⁸³ Joint Satellite and Terrestrial Use of Spectrum, IEEE ComSoc presentation by Dick Evans, Senior Engineer Mobile Satellite Ventures, October 26, 2004

⁸⁴ Michel G. Gelinas, Mike Durkin, General Dynamics C4 Systems, Satellite-Based Air Ground Communications Concepts For Air Traffic Services, August 16, 2004 response to NASA RFI, p. 4

⁸⁵ Daniel Schwartz, Director Transportation Market, Iridium Satellite, LLC, Iridium System and Services Overview, PowerPoint Presentation, July 2004, Slide 14.

⁸⁶ The European Union funded program, code named “Anastasia” may in fact produce avionics for this service that are affordable by General Aviation users. Time will tell.

⁸⁷ “VDL2 Frequency Planning Results”, Desperier, B. and Delhaise P., Eurocontrol, p.5, sect. 5, Table 4, available on Eurocontrol Mode 2 web site.

⁸⁸ “VDL Mode E VHF Aeronautical Communications Using Digital TDMA On 8.33 kHz Channels”, VDL Mode E White Paper—May 2004—Copyright © Rockwell Collins Inc.

⁸⁹ “Single Antenna Cochannel Interference Cancellation in Asynchronous TDMA Systems”, technical paper available from University through web, Schoenich H., Hoeher P., University of Kiel, p.1.

⁹⁰ From Aeronautical Communications Panel (AMCP) Working Paper AMCP/8-WP25, p.11.

⁹¹ From Aeronautical Communications Panel (AMCP) Working Paper AMCP/8-WP25, p.10.

⁹² Minimum Aviation System Performance Standards (MASPS), RTCA-DO224, Change 2, dated Aug. 27, 2002, RTCA, Inc.

⁹³ “Aspects of Implementation of point-to-point communications”, NEAN Update Programme Phase 2 website, Chapter 6, Appendix E, p.3, www.nup.nu/docs/master/ch_6_app_e.pdf

⁹⁴ We are slightly changing SNR numerically and changing the input reference to the detector to avoid having to discuss receiver implementation losses. We also want to avoid a more involved calculation or reference to Mode E SNR since it is technically a little more involved with the effect of $\alpha = 0.3$ compared to Modes 2 and 3 with 0.6, which prevents a simple scaling of bandwidths in the SNR calculation. We simply will use Rockwell-Collins published Mode E improvement factor of 3 dB due to bit rate scaling alone.

⁹⁵ Minimum Aviation System Performance Standards (MASPS), RTCA-DO224, Change 2, dated Aug. 27, 2002, RTCA, Inc., Appendix K.

⁹⁶ “Aspects of Implementation of point-to-point communications”, NEAN Update Programme Phase 2 website, Chapter 6, Appendix E, p.9, www.nup.nu/docs/master/ch_6_app_e.pdf

⁹⁷ from NEAN Update Programme Phase 2 website, www.nup.nu

⁹⁸ ¹¹ Briefing to RTCA SC172, 15 April 1998, ATM Department of the SOFREAVIA Group.

⁹⁹ Automatic Dependent Surveillance Broadcast (ADS-B) Mode S Extended Squitter, Dr. Vincent A. Orlando, MIT Lincoln Laboratory, FAA web site, http://adsb.tc.faa.gov/WG3_Meetings/Meeting8/Squitter-Lon.pdf, Slide 9.

¹⁰⁰ *ibid.*, Slide 10.

¹⁰¹ *ibid.*, Slide 16.

¹⁰² *ibid.*, Slide 23.

¹⁰³ Assumptions used were as follows: 1. DoD clears 960 to 1224 MHz band using 14-frequency remapping capability. 2. FAA Clears all DMEs from 960-1224 MHz band and Link 16 is hopped over the 14 remapped frequencies in FAA system (at 3 MHz intervals) from 969-1008 MHz. 3. Voice is transmitted using current DoD 16 kbps CVSD voice algorithm, and Packed-2 double pulse transmission (for robustness and resistance to multipath), which allows 7 + time-slot block allocations (nearly 8) per Link 16 net for voice (a 16 kbps voice channel with Packed-2 currently occupies slightly more than 13 % of a net). 4. The 30 nets number is an approximation based on a MITRE analysis performed in the 70s that shows that 20 nets can be supported with minimal jam resistance degradation in the same geographic area; and over 100 nets can be supported while still maintaining full performance without the presence of jamming. This was based on hopping over the full 51 frequencies. Thus approximately 14/51 of this or 27 + nets can be supported with 14 frequencies (with the same pulse density as 100 nets with 51 frequencies), since it was assumed that FAA would not require jam resistance. We rounded the numbers to 8 and 30 as an approximation.

¹⁰⁴ The authors do not discount the importance of the HF Data Link as a current and operational system. We expect this system to be operational for the foreseeable future, and to be an important component of A/G communications, providing data services in remote regions. The “No” in the “Evaluate” column simply indicates that the system is clearly not a solution for congestion in the VHF Band, which is a primary driver for this study. It does not and can not provide additional voice channels.

¹⁰⁵ The Advanced Airport Data Link (ADL) did not score well because of a lack of technical maturity, lack of standards, and no direct air-to-air (or in the case of surface applications, vehicle-to-vehicle) functional capability. Yes, it can provide high data rates to many users, but WCDMA and 802.16e also provide high data rates while enjoying the advantages of being technically mature and standardized systems. A caveat is in order for surface applications, which may change the eventual scoring of 802.16e and WCDMA. Should the surface needs extend to aircraft landing and departure, then whatever technology that is adopted will have to exhibit acceptable BER performance at vehicle speeds that are quite high. The recommended approach for future analysis is to

characterize the airport propagation environment, and simulate the BER performance of the recommended commercial technologies. Failure of the commercial standards to provide acceptable performance would have the consequence of raising ADL status as a viable surface candidate.

¹⁰⁶ This includes areas like the Gulf of Mexico, where terrestrial infrastructure can not provide radio coverage.

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13. ABSTRACT (Maximum 200 words) To address emerging saturation in the VHF aeronautical bands allocated internationally for air traffic management communications, the International Civil Aviation Organization (ICAO) has requested development of a common global solution through its Aeronautical Communications Panel (ACP). In response, the Federal Aviation Administration (FAA) and Eurocontrol initiated a joint study, with the support of NASA and U.S. and European contractors, to provide major findings on alternatives and recommendations to the ICAO ACP Working Group C (WG-C). Under an FAA/Eurocontrol cooperative research and development agreement, ACP WG-C Action Plan 17 (AP-17), commonly referred to as the Future Communications Study (FCS), NASA Glenn Research Center is responsible for the investigation of potential communications technologies that support the long-term mobile communication operational concepts of the FCS. This report documents the results of the first phase of the technology assessment and recommendations referred to in the Technology Pre-Screening Task 3.1 of AP-17. The prescreening identifies potential technologies that are under development in the industry and provides an initial assessment against a harmonized set of evaluation criteria that address high level capabilities, projected maturity for the time frame for usage in aviation, and potential applicability to aviation. A wide variety of candidate technologies were evaluated from several communications service categories including: cellular telephony; IEEE-802.xx standards; public safety radio; satellite and over-the-horizon communications; custom narrowband VHF; custom wideband; and military communications.				
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